Distributed Systems

CS425/ECE428

Instructor: Radhika Mittal

Acknowledgements for some of materials: Indy Gupta and Nikita Borisov

Logistics

- MP0 is due today at 11:59pm.

- Reminder to share your name when you speak up in class.

- Feb 7 lecture was not recorded! Please see my Campuswire post for links to last year's videos covering the same topic.

Today's agenda

- Global State (contd.)
  - Chapter 14.5
- Multicast
  - Chapter 15.4

Today's agenda

- **Global State (contd.)**
  - Chapter 14.5
- **Multicast**
  - Chapter 15.4

Global Snapshot Summary

- The ability to calculate global snapshots in a distributed system is very important.
- But don't want to interrupt running distributed application.
- Chandy-Lamport algorithm calculates global snapshot.
- Obeys causality (creates a consistent cut).

Chandy-Lamport Algorithm: Properties

- Any run of the Chandy-Lamport Global Snapshot algorithm creates a consistent cut.
- Let $\mathbf{e}_i$ and $\mathbf{e}_j$ be events occurring at $\mathbf{p}_i$ and $\mathbf{p}_j$, respectively such that
  - $\mathbf{e}_i \rightarrow \mathbf{e}_j$ ($\mathbf{e}_i$ happens before $\mathbf{e}_j$)
- The snapshot algorithm ensures that

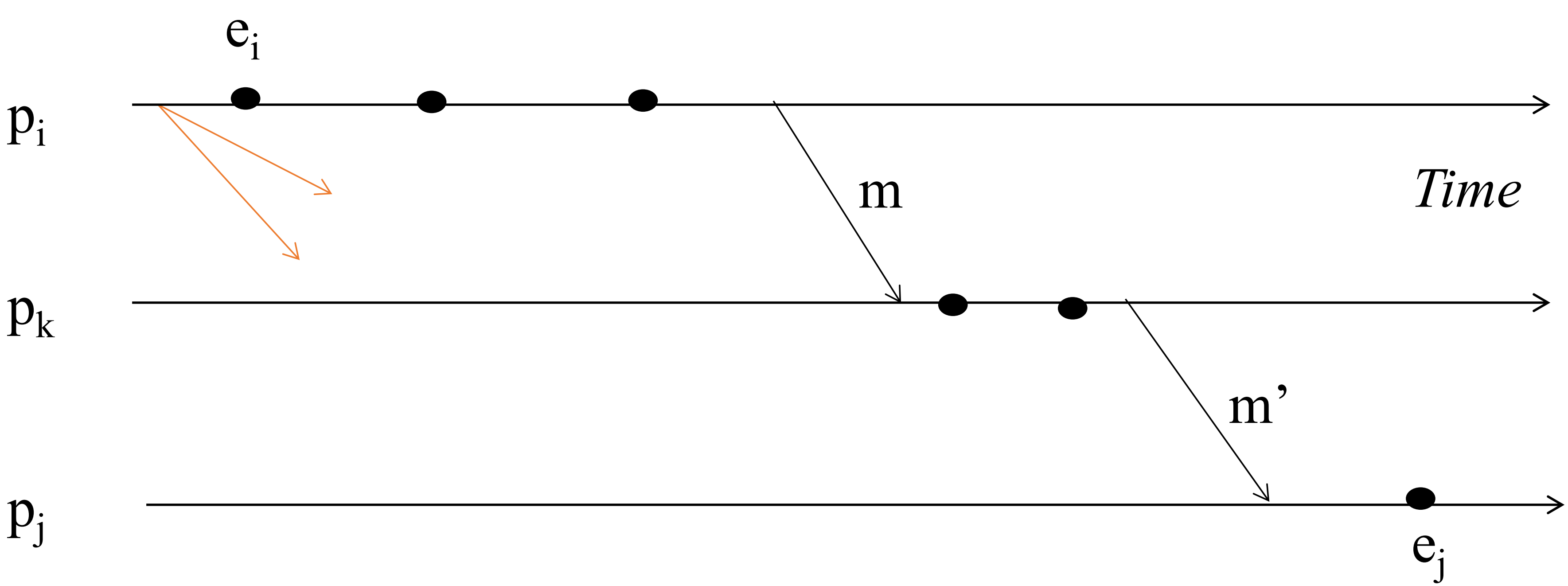
  if $\mathbf{e}_j$ is in the cut then $\mathbf{e}_i$ is also in the cut.

- That is: if $\mathbf{e}_j \rightarrow$ < $\mathbf{p}_j$ records its state>, then

  it must be true that $\mathbf{e}_i \rightarrow$ <$\mathbf{p}_i$ records its state>.

Chandy-Lamport Algorithm: Properties

- If $\mathbf{e_j} \rightarrow$ < $\mathbf{p_j}$ records its state>, then
  it must be true that $\mathbf{e_i} \rightarrow$ <$\mathbf{p_i}$ records its state>.
- By contradiction, *suppose* $\mathbf{e_j} \rightarrow$ *< p_j records its state>, and <p_i records its state>* $\rightarrow \mathbf{e_i}$.



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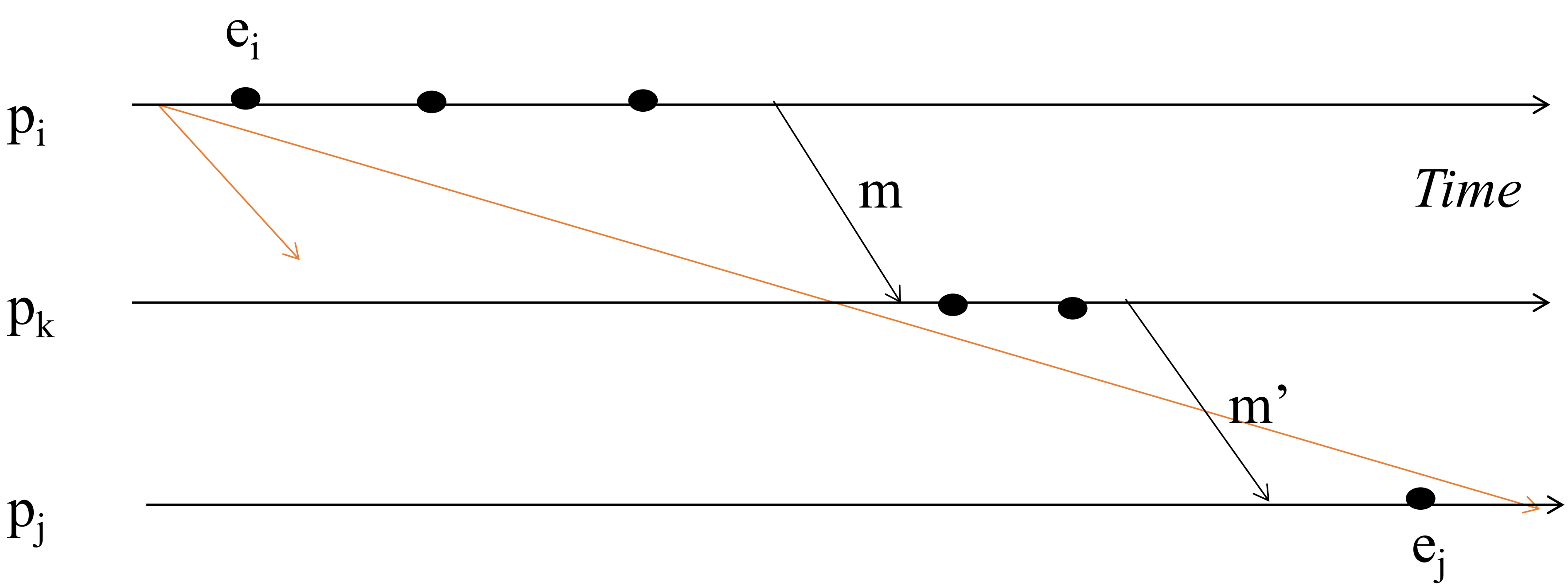

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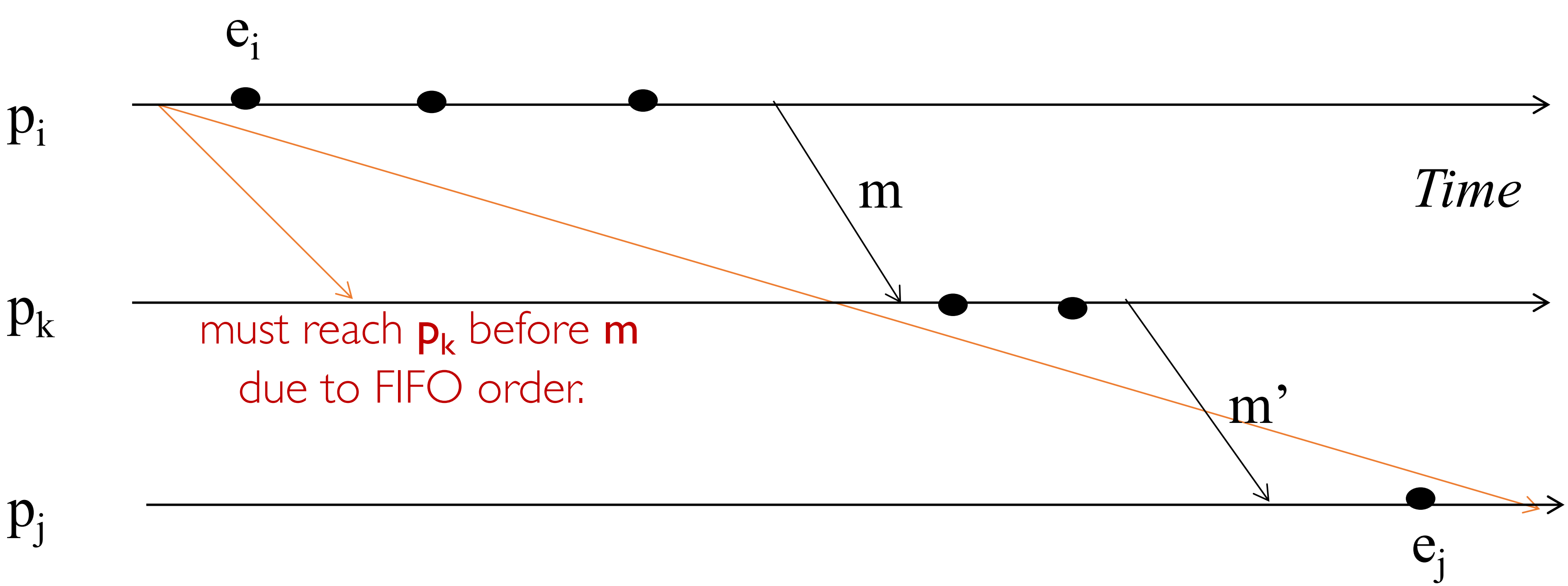

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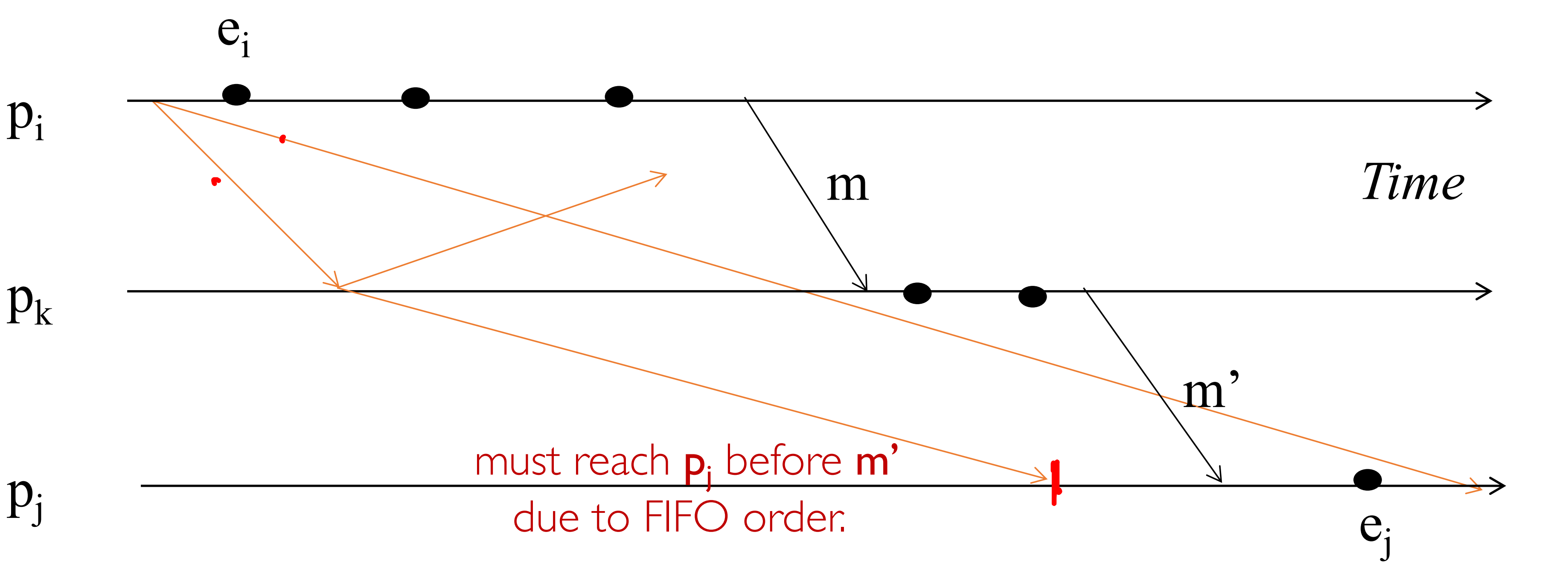

Chandy-Lamport Algorithm: Properties

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- By contradiction, *suppose* $\mathbf{e_j}$ → *<* $\boldsymbol{p_j}$ *records its state>, and <*$\boldsymbol{p_i}$ *records its state>* → $\mathbf{e_i}$.
- Consider the path of app messages (through other processes) that go from $\mathbf{e_i}$ to $\mathbf{e_j}$.
- Due to FIFO ordering, markers on each link in above path will precede regular app messages.
- Thus, since <$\mathbf{p_i}$ records its state> → $\mathbf{e_i}$, it must be true that $\mathbf{p_j}$ received a marker before $\mathbf{e_j}$.
- Thus $\mathbf{e_j}$ is not in the cut => contradiction.

Why capture global snapshots?

- *Checkpointing* the system state.
- Reasoning about unreferenced objects (for garbage collection).
- Distributed debugging.
- Can be used to detect **global properties.**
    - **Safety vs. Liveness**

Revisions: notations and definitions

- For a process p_i , where events $e_i^1, \ldots$ occur:

  history(p_i) = $h_i = <e_i^1, \ldots >$

  prefix history(p_i^k) = $h_i^k = <e_i^1, \ldots, e_i^k >$

  s_i^k : p_i's state immediately after k^{th} event.

- For a set of processes $<p_1, p_2, p_3, \ldots, p_n>$:

  global history: $H = \cup_i (h_i)$

  a cut $C \subseteq H = h_1^{c_1} \cup h_2^{c_2} \cup \ldots \cup h_n^{c_3}$

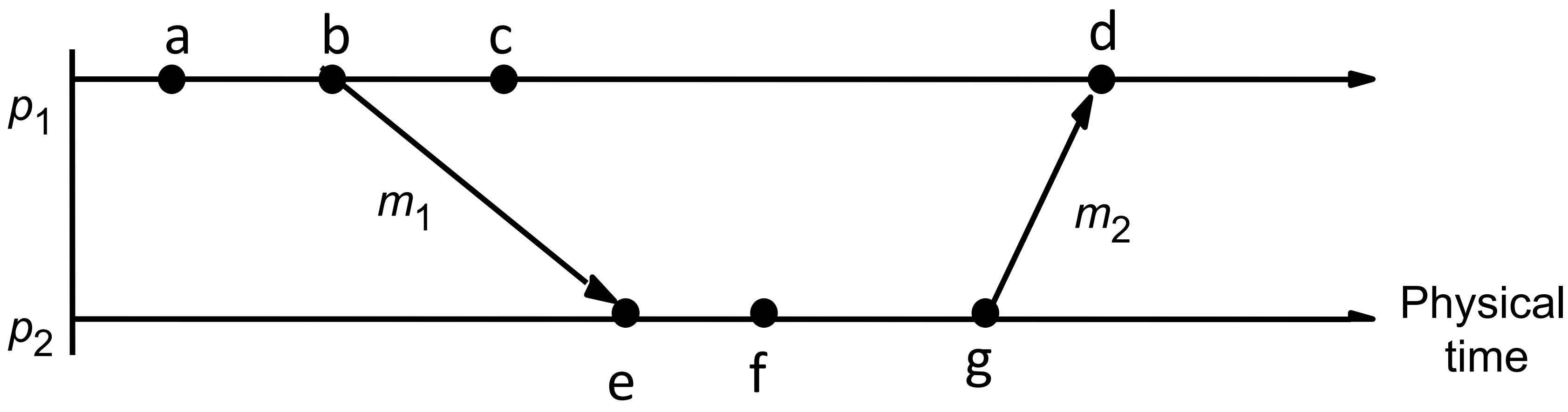
  the frontier of $C = \{e_i^{c_i}, i = 1,2, \ldots n\}$

  global state S that corresponds to cut $C = \cup_i (s_i^{c_i})$

More notations and definitions

- A **run** is a total ordering of events in H that is consistent with each $\mathbf{h_i}$'s ordering.
- A **linearization** is a run consistent with happens-before ($\rightarrow$) relation in H.

Example



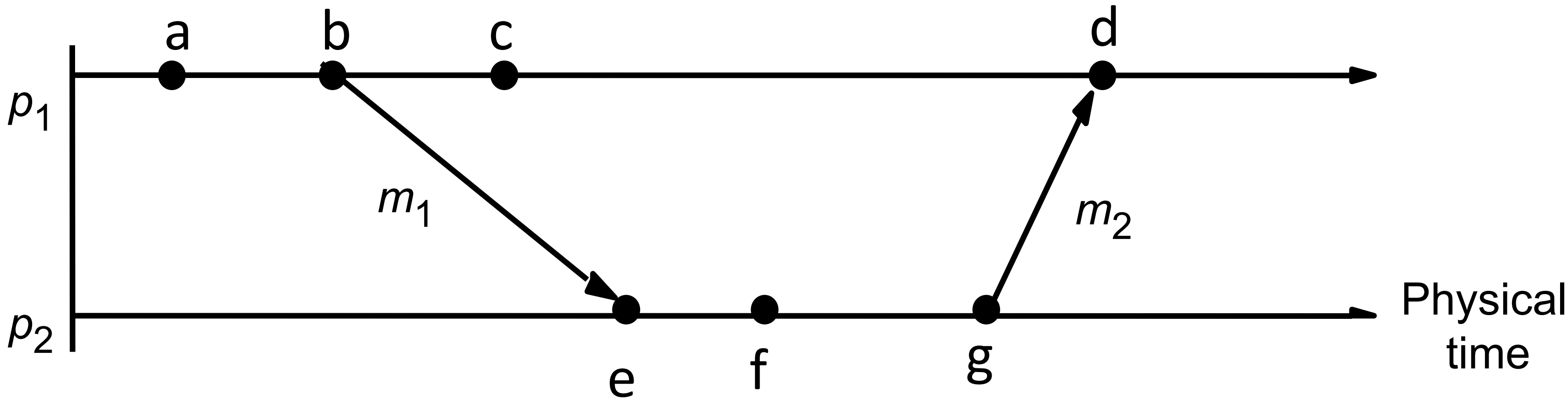
Order at p_1: < a, b, c, d >   Order at p_2: < e, f,g>

Causal order across p_1 and p_2: < b, e> , <g , d >

Run: < a, b, c, d , e, f, g>

Linearization: <a, b, c, e, f, g , d >

Example



< a, b, e, f, c, g , d >:

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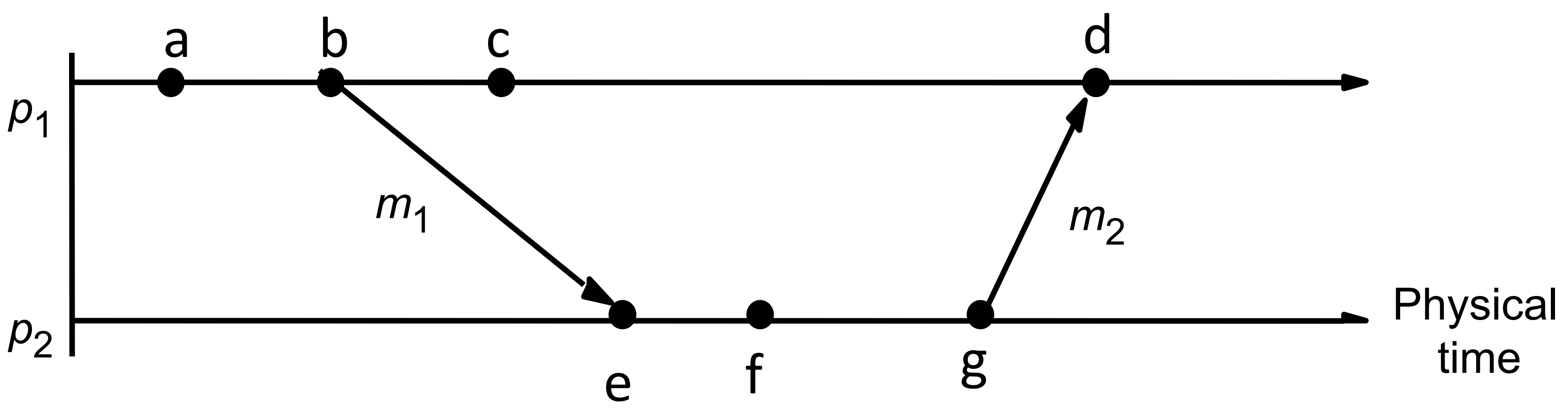
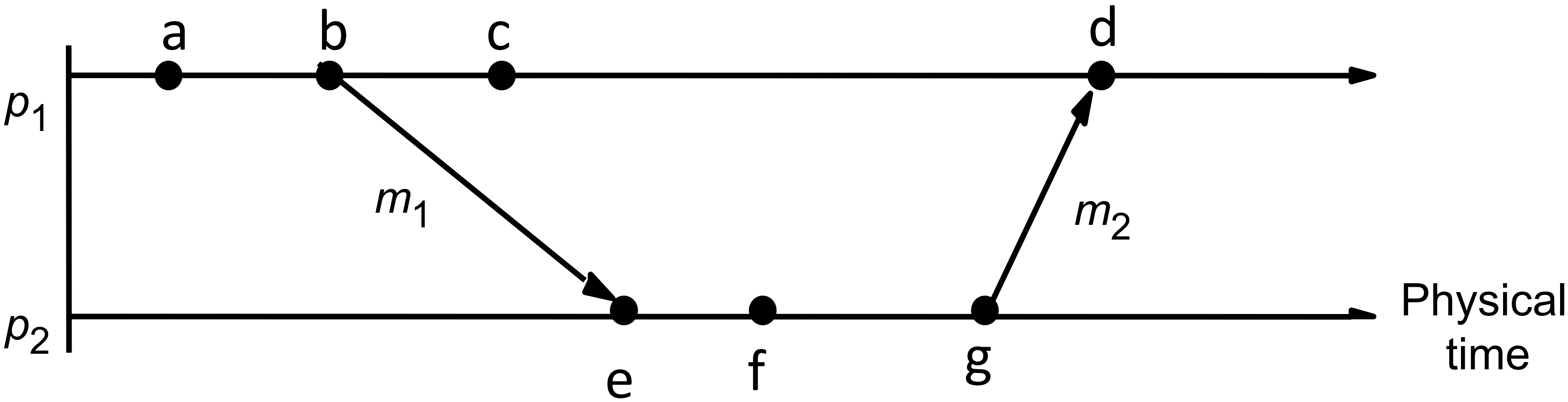


< a, b, e, f, c, g , d >: Linearization

Example



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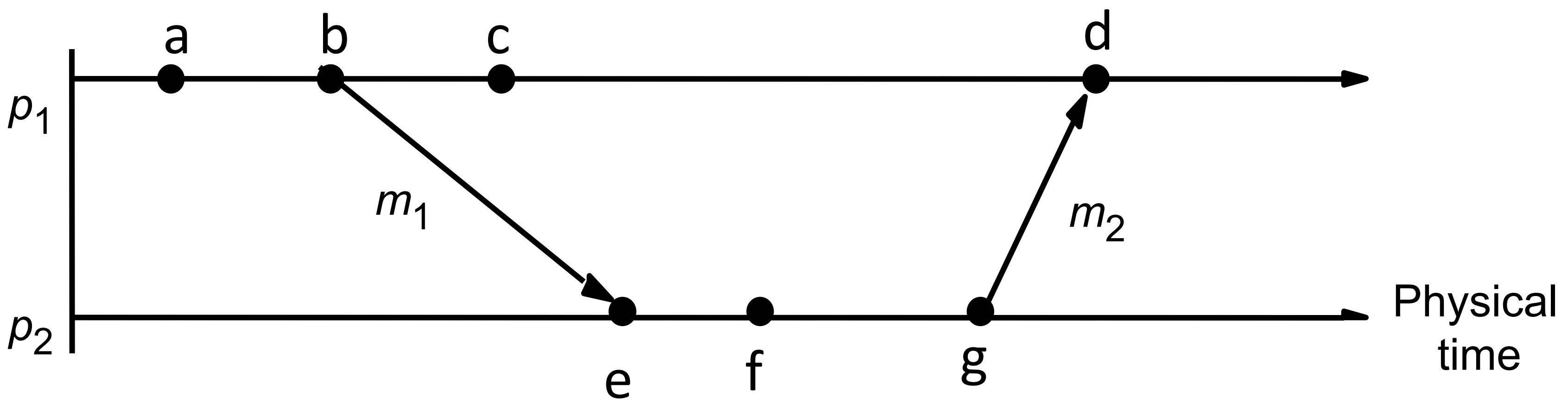

< a, f, e , b, c, g , d >: Not even a run

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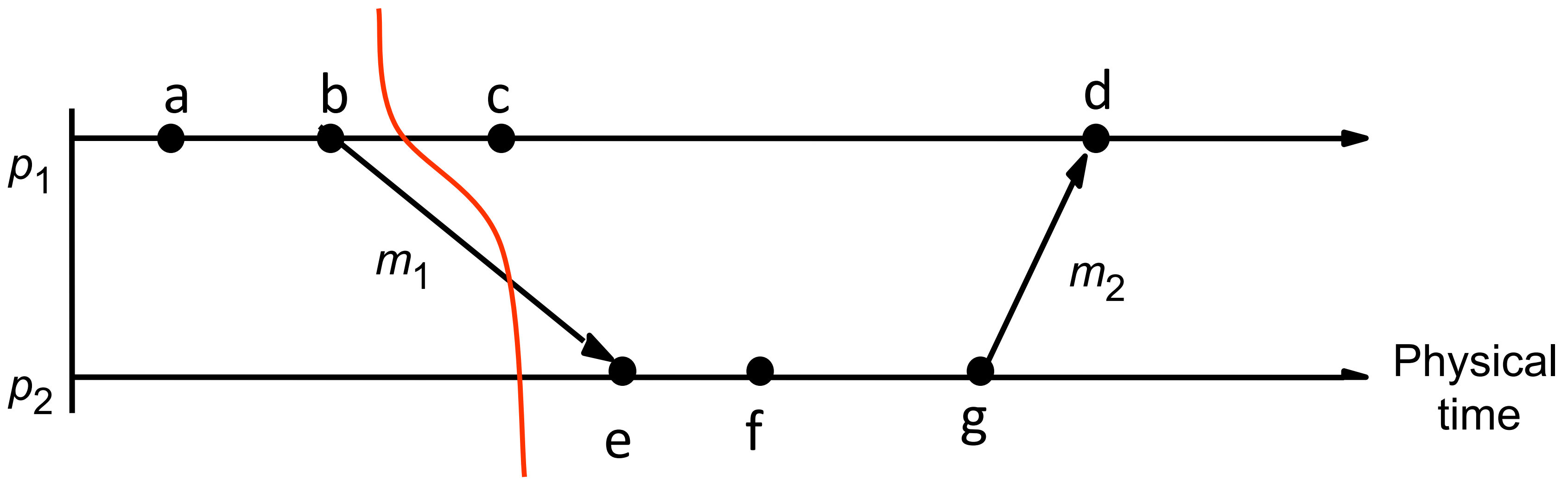
- Linearizations pass through consistent global states.

Example



Linearization: < a, b, c, e, f, g , d >

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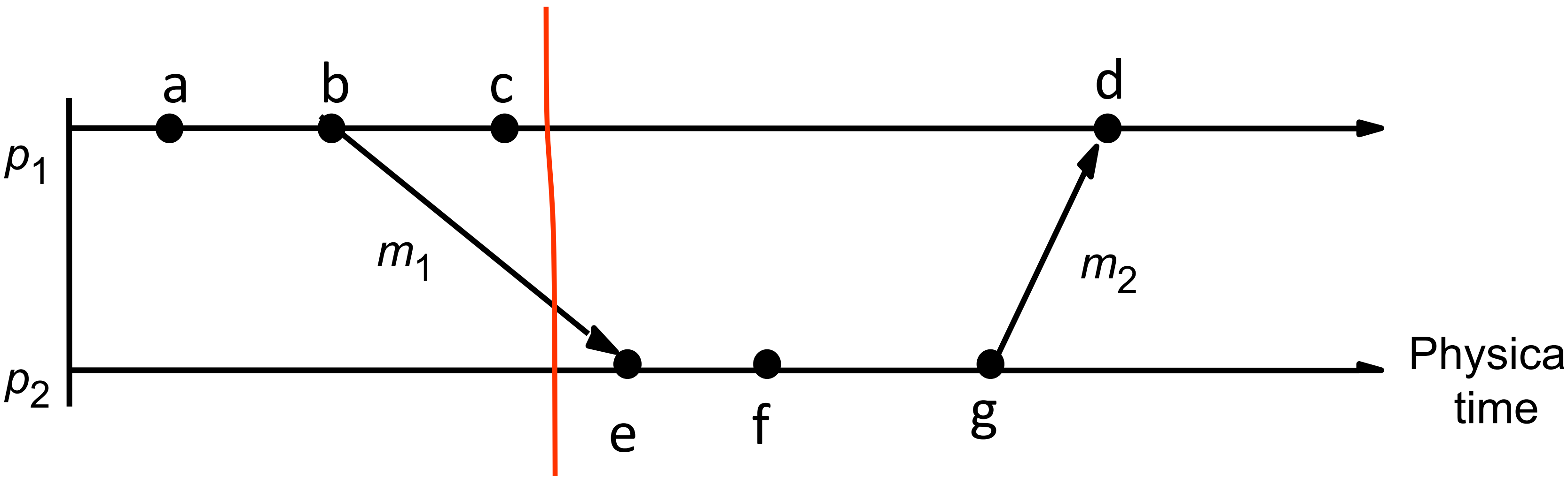

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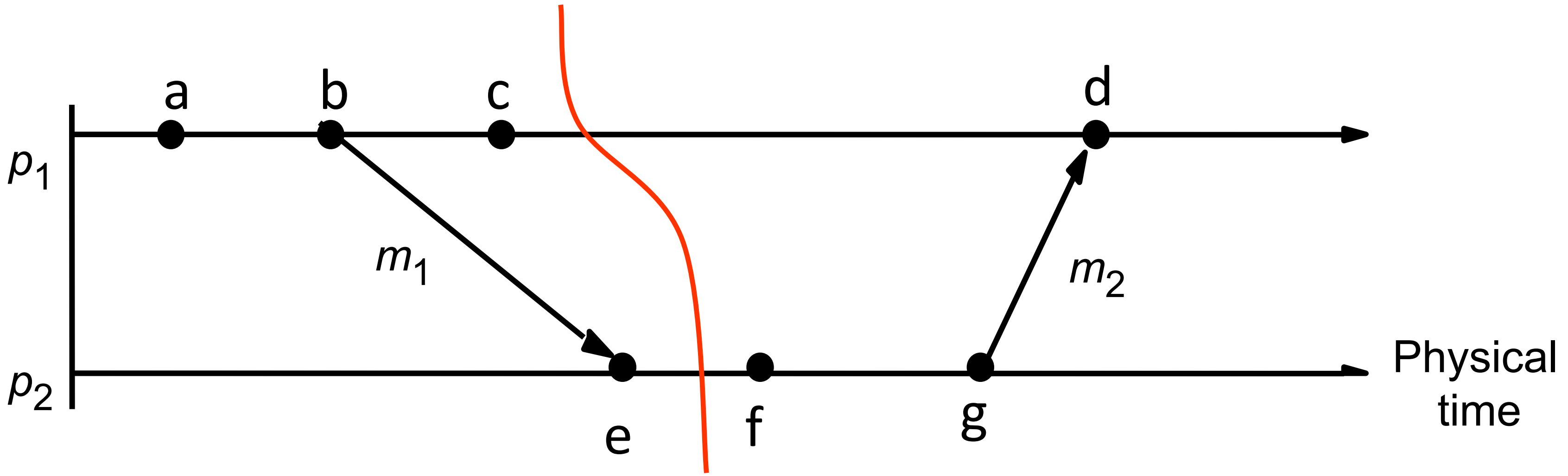

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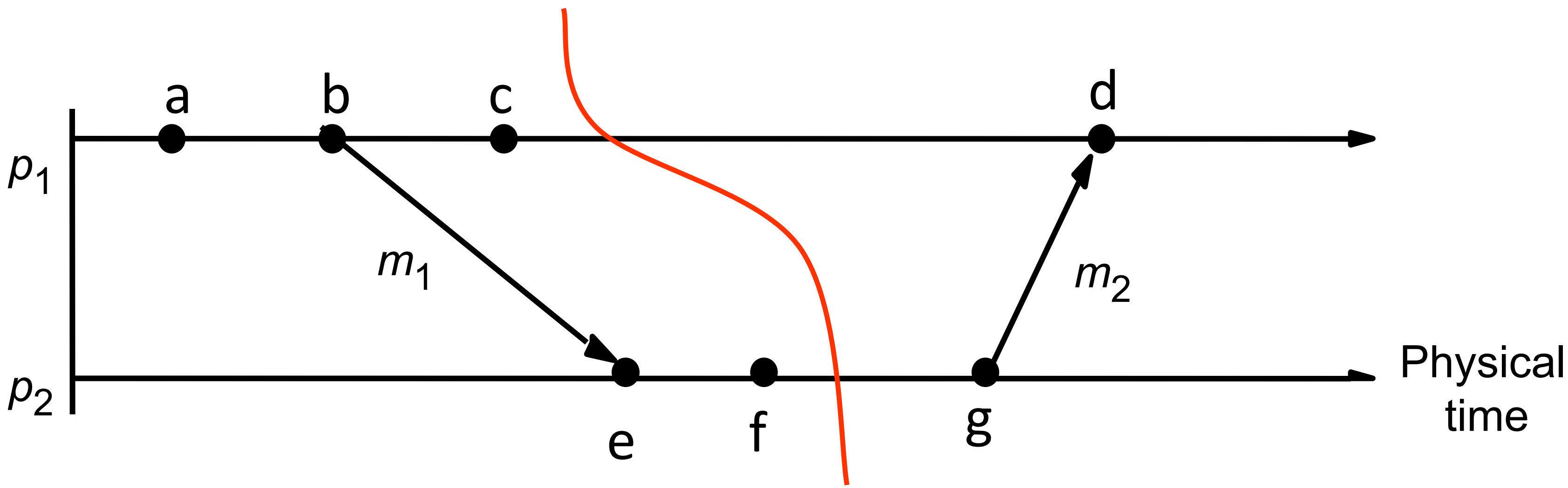

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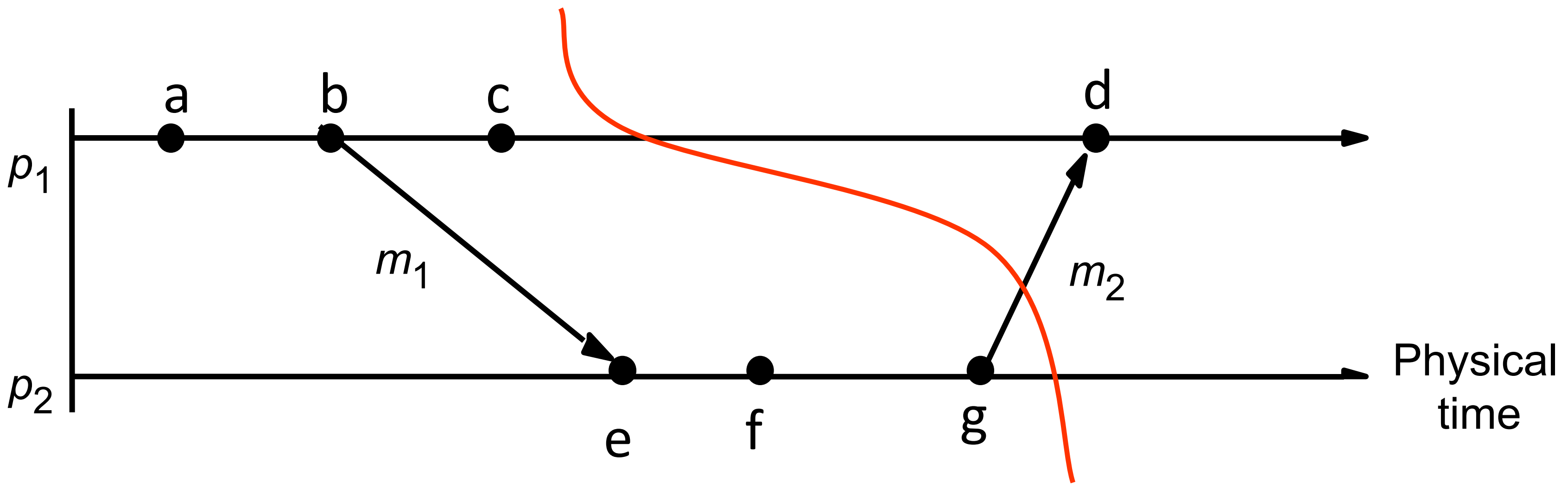

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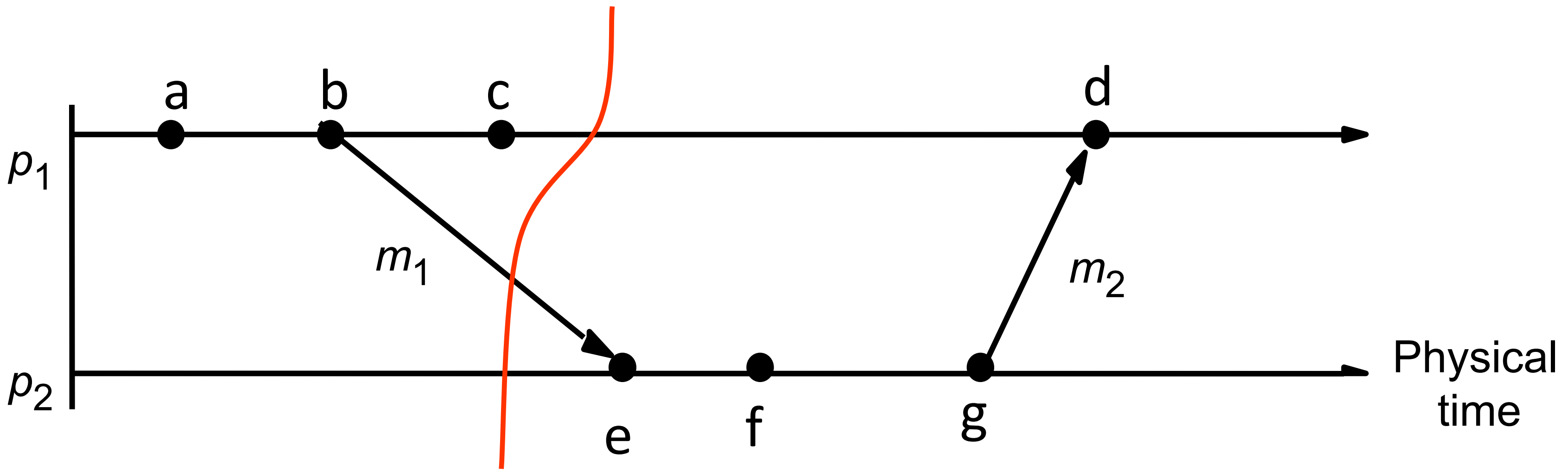

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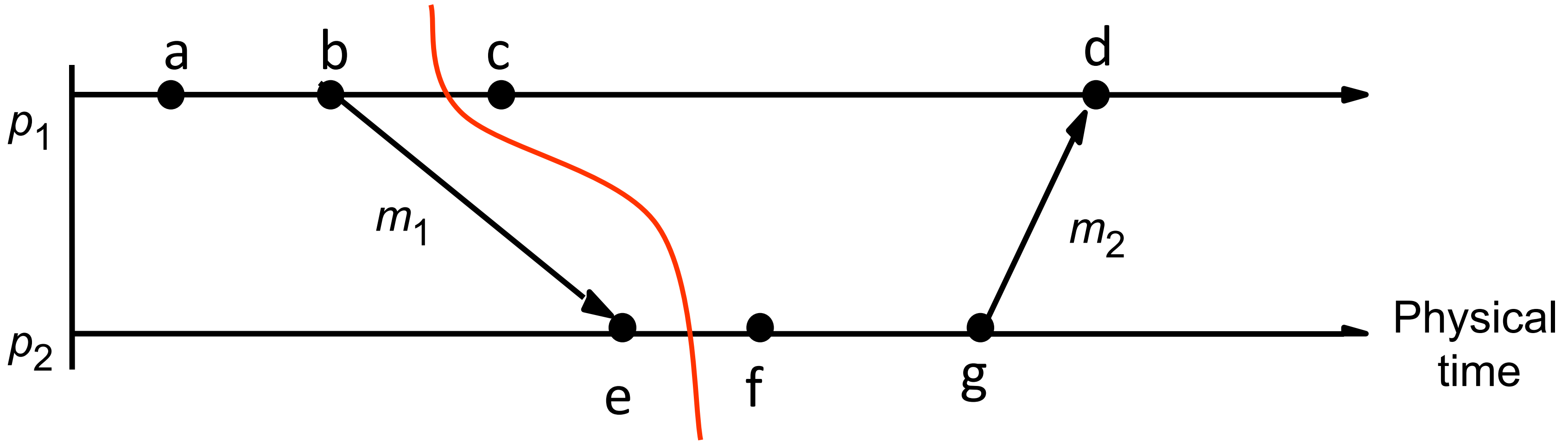

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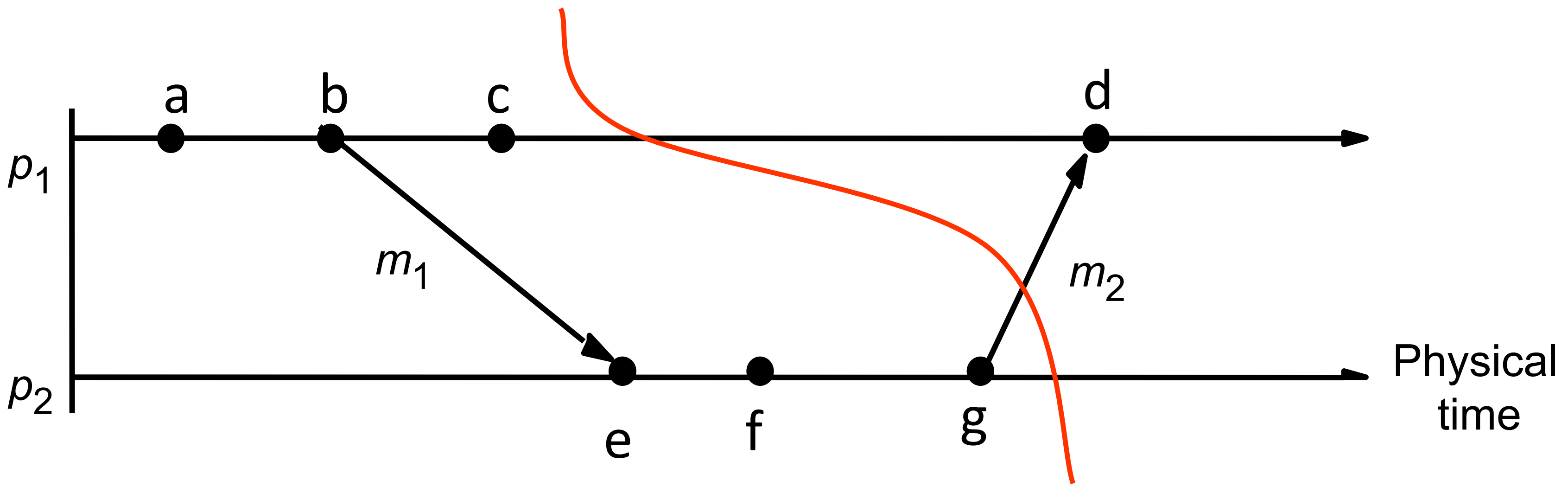

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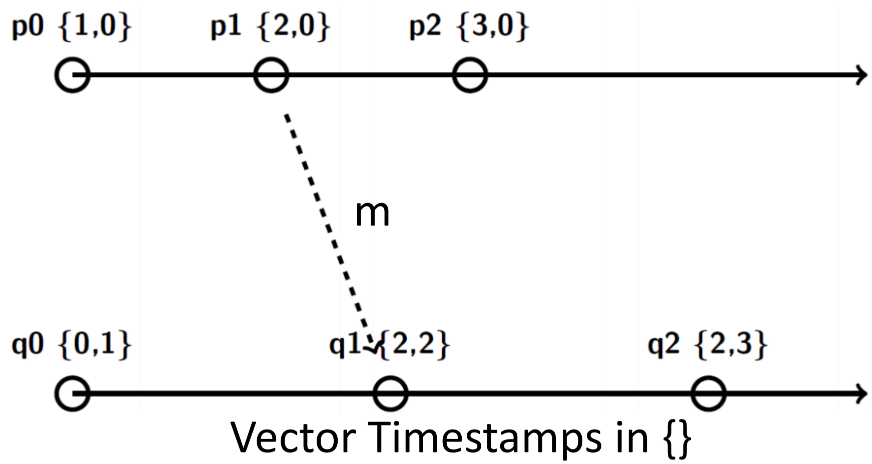
- A run is a total ordering of events in H that is consistent with each $\mathbf{h_i}$'s ordering.
- A linearization is a run consistent with happens-before ($\rightarrow$) relation in H.
- Linearizations pass through consistent global states.
- A global state $\mathbf{S_k}$ is reachable from global state $\mathbf{S_i}$, if there is a linearization that passes through $\mathbf{S_i}$ and then through $\mathbf{S_k}$.
- The distributed system evolves as a series of transitions between global states S_0 , S_1 , ….

State Transitions: Example



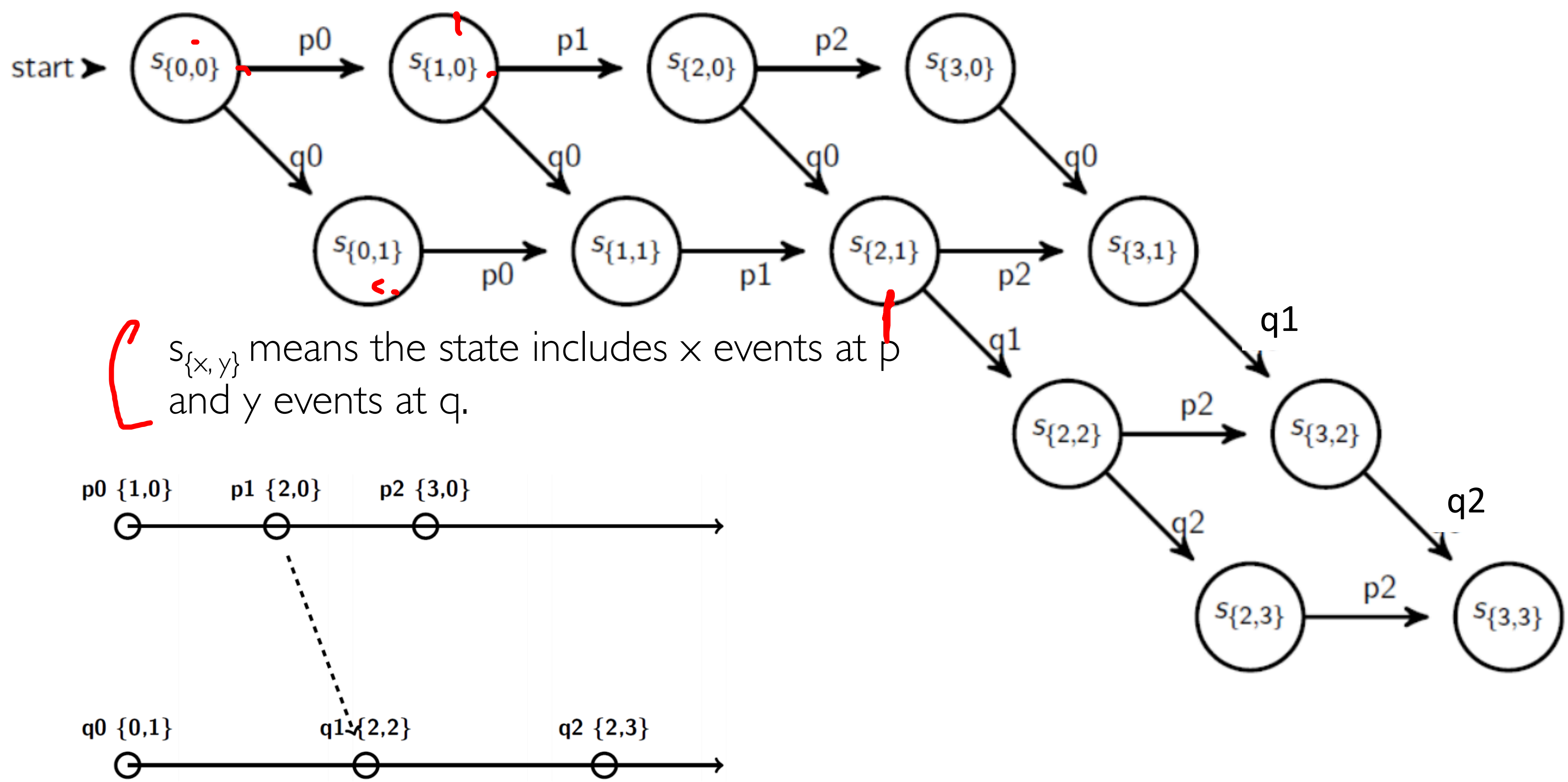
Many linearizations:

- < p0, p1, p2, q0, q1, q2>
- < p0, q0, p1, q1, p2, q2>
- <q0, p0, p1, q1, p2, q2 >
- <q0, p0, p1, p2, q1,q2 >
- ……

- Causal order:
  - p0 → p1 → p2
  - q0 → q1 → q2
  - p0 → p1 → q1 → q2
- Concurrent:
  - p0 || q0
  - p1 || q0
  - p2 || q0, p2 || q1, p2 || q2

State Transitions: Example

Execution Lattice. Each path represents a linearization.



$s_{\{x, y\}}$ means the state includes x events at p and y events at q.

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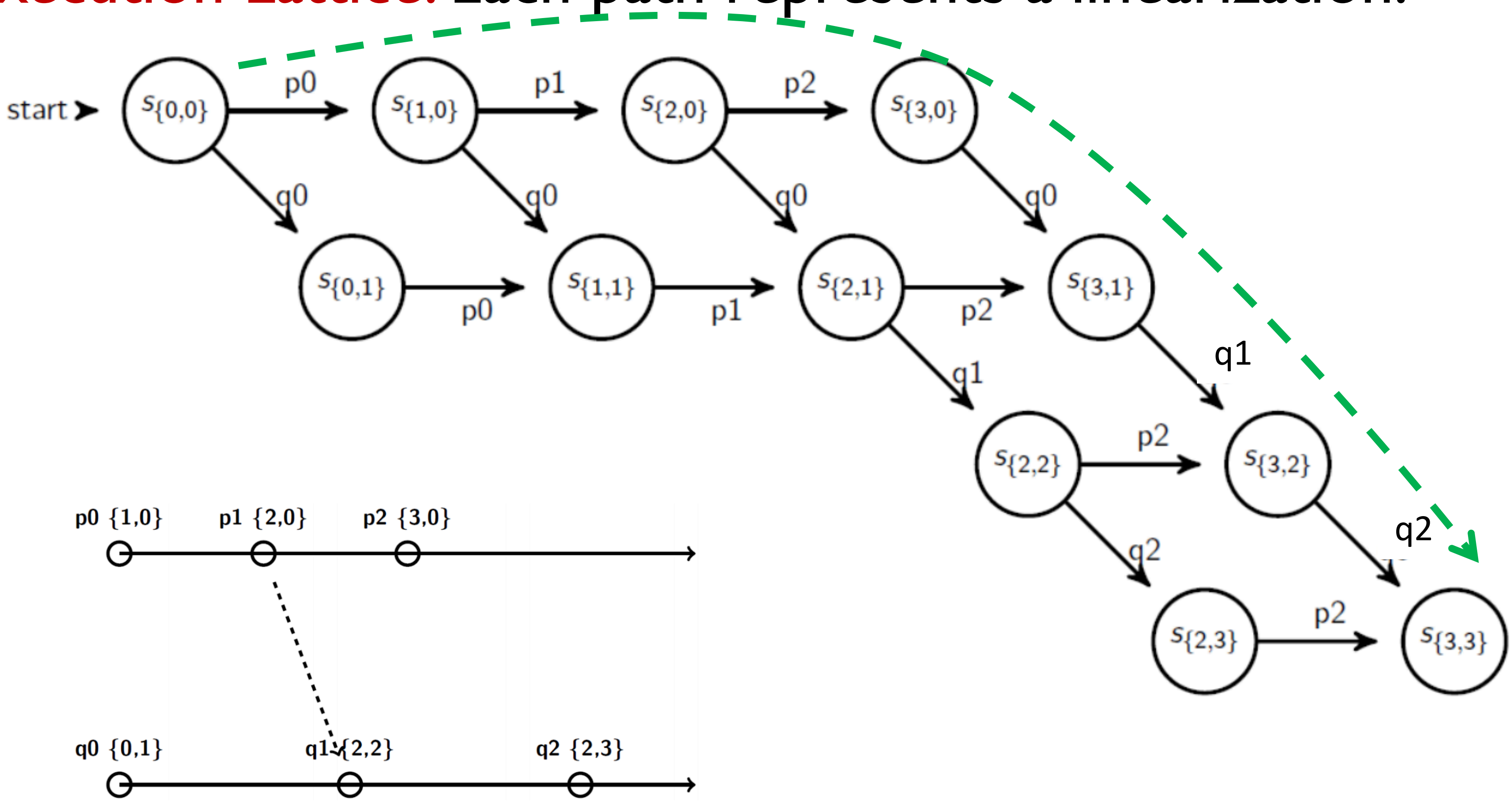

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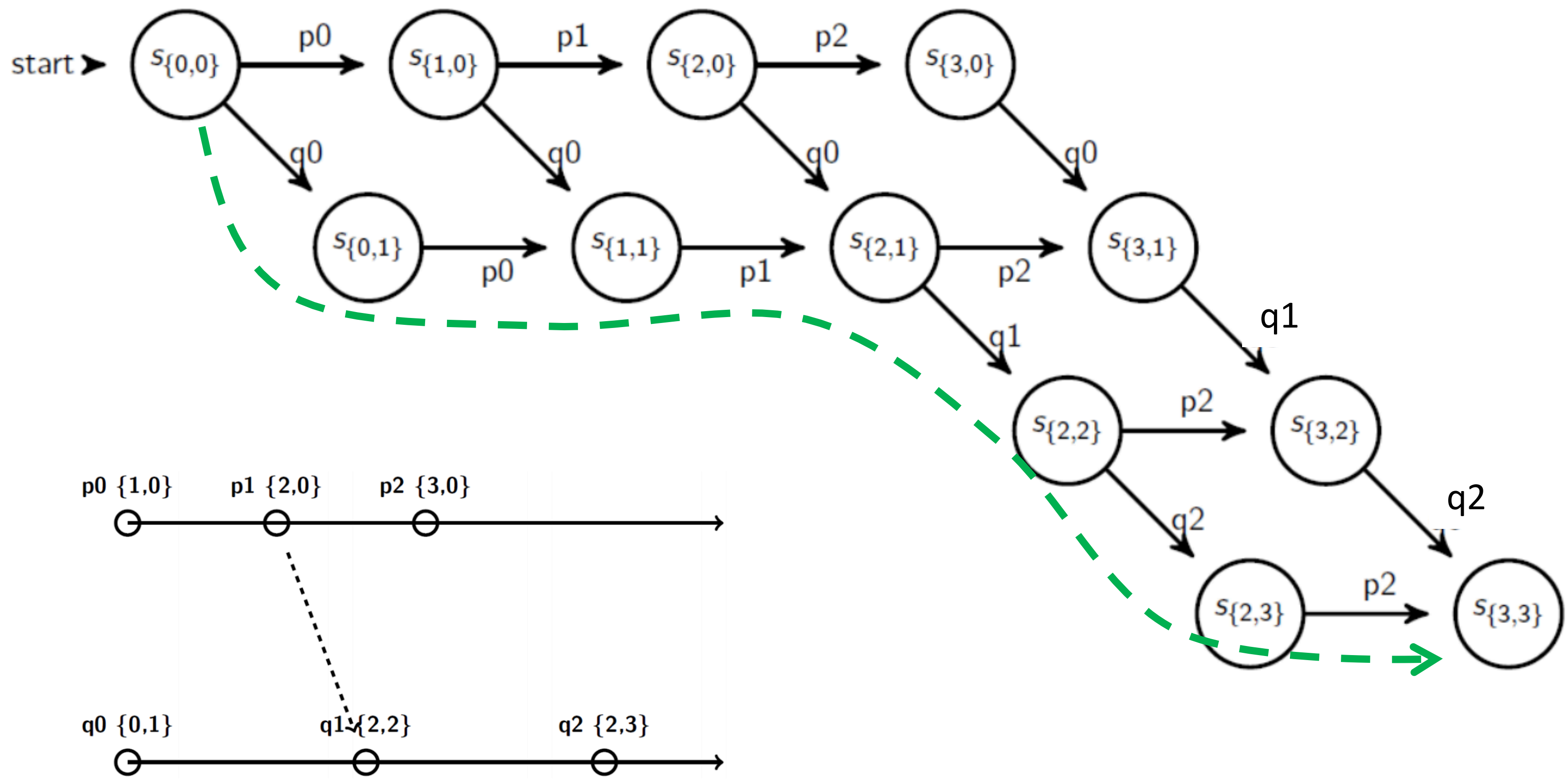

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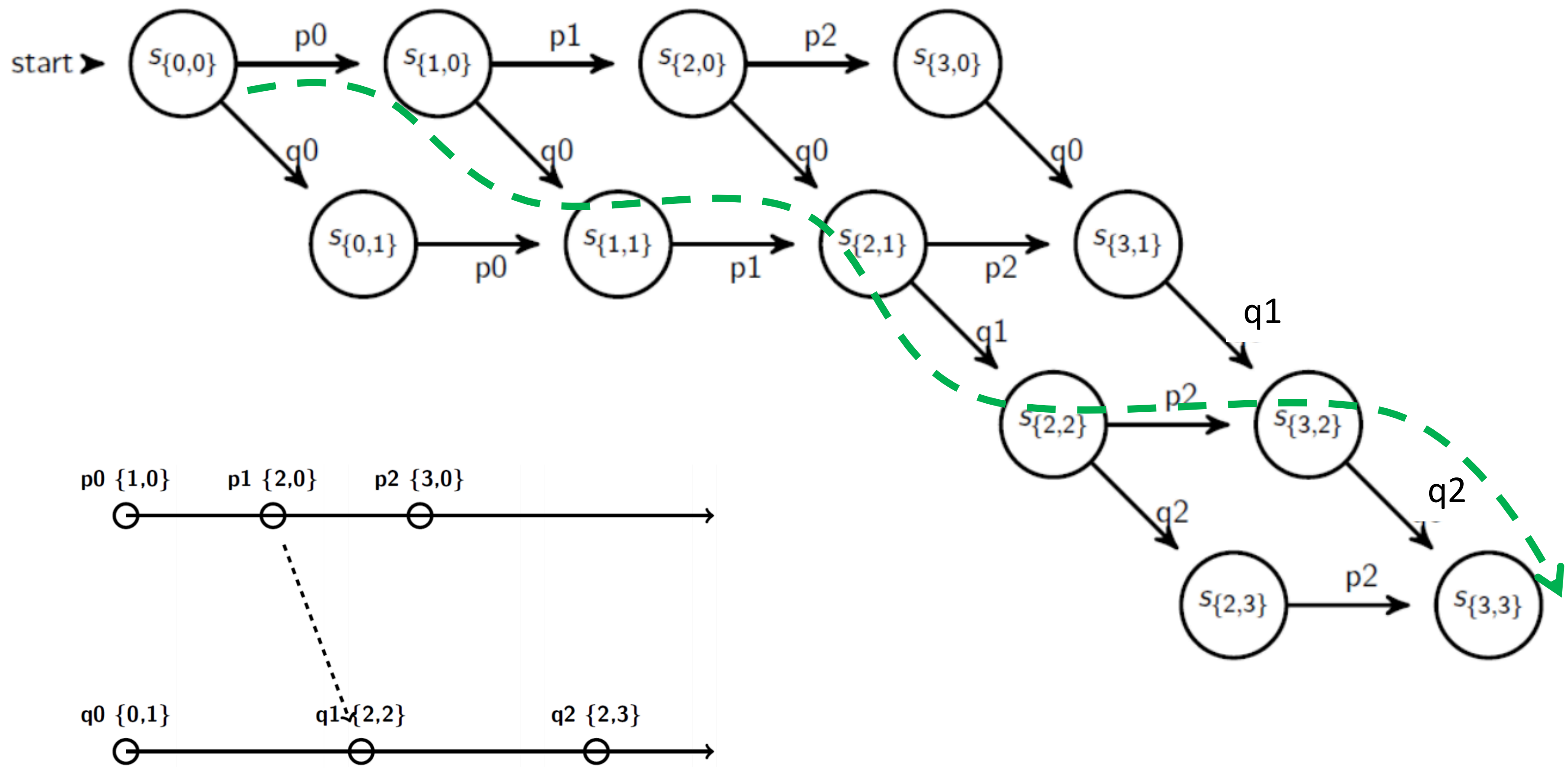

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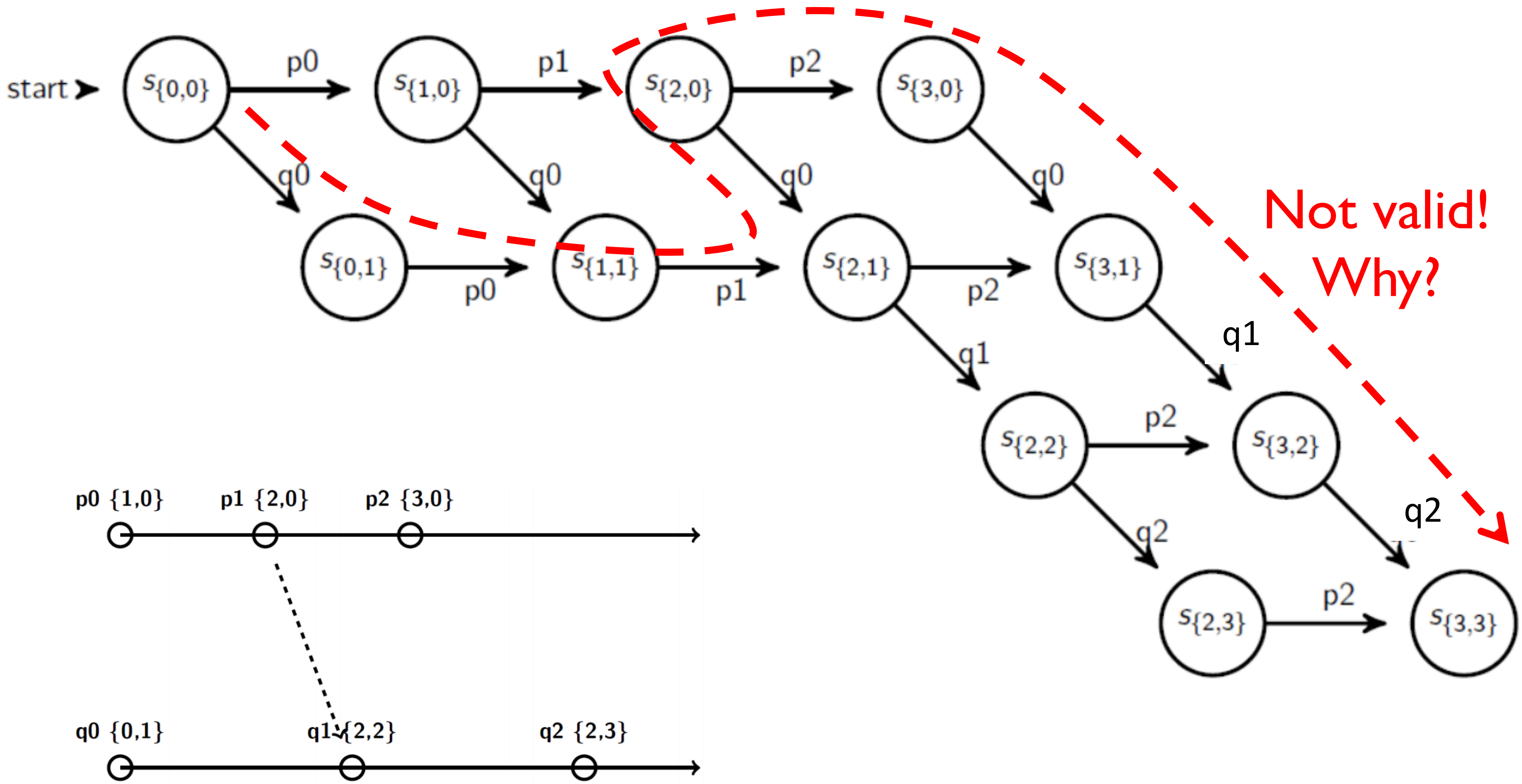

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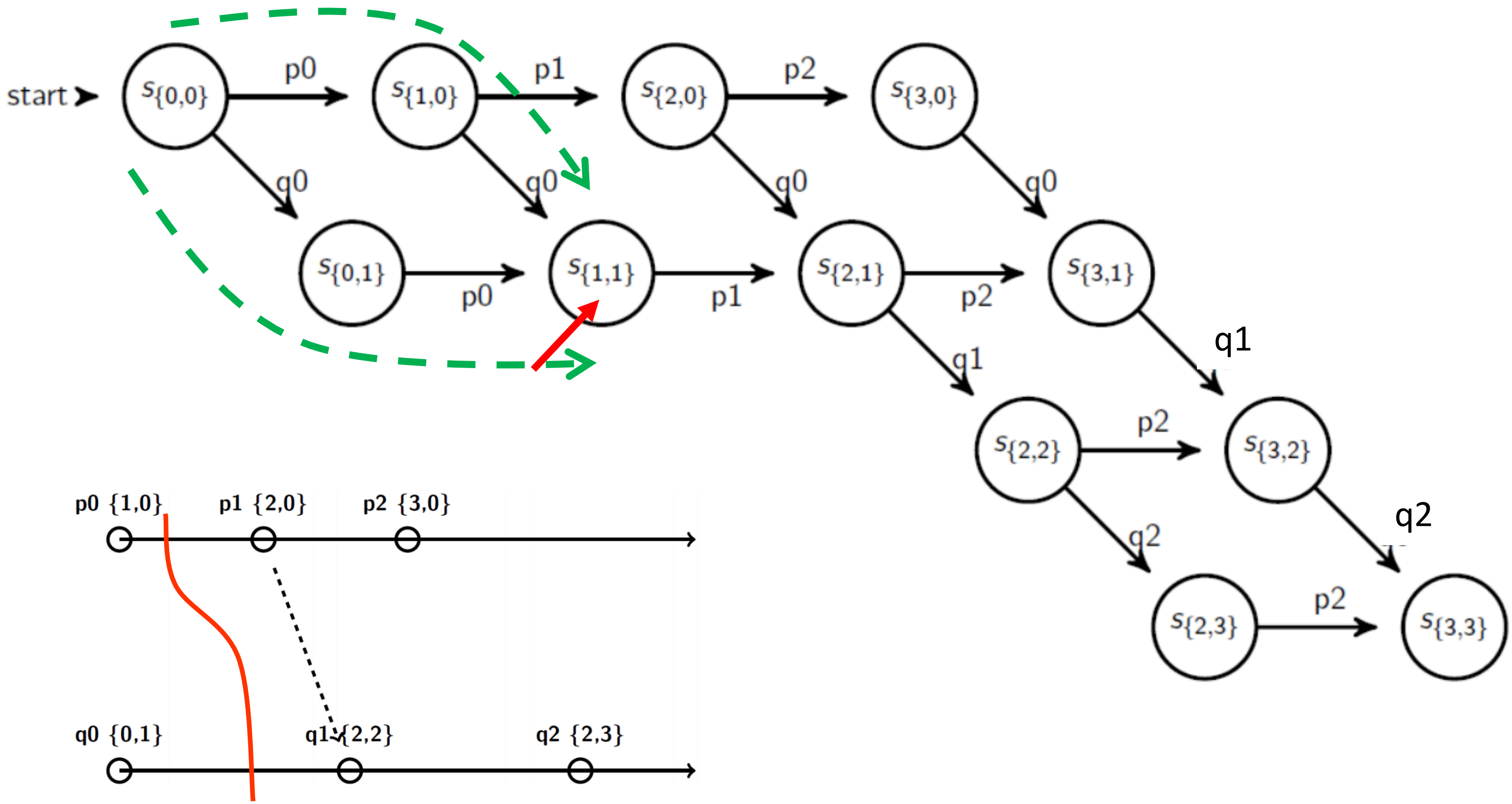

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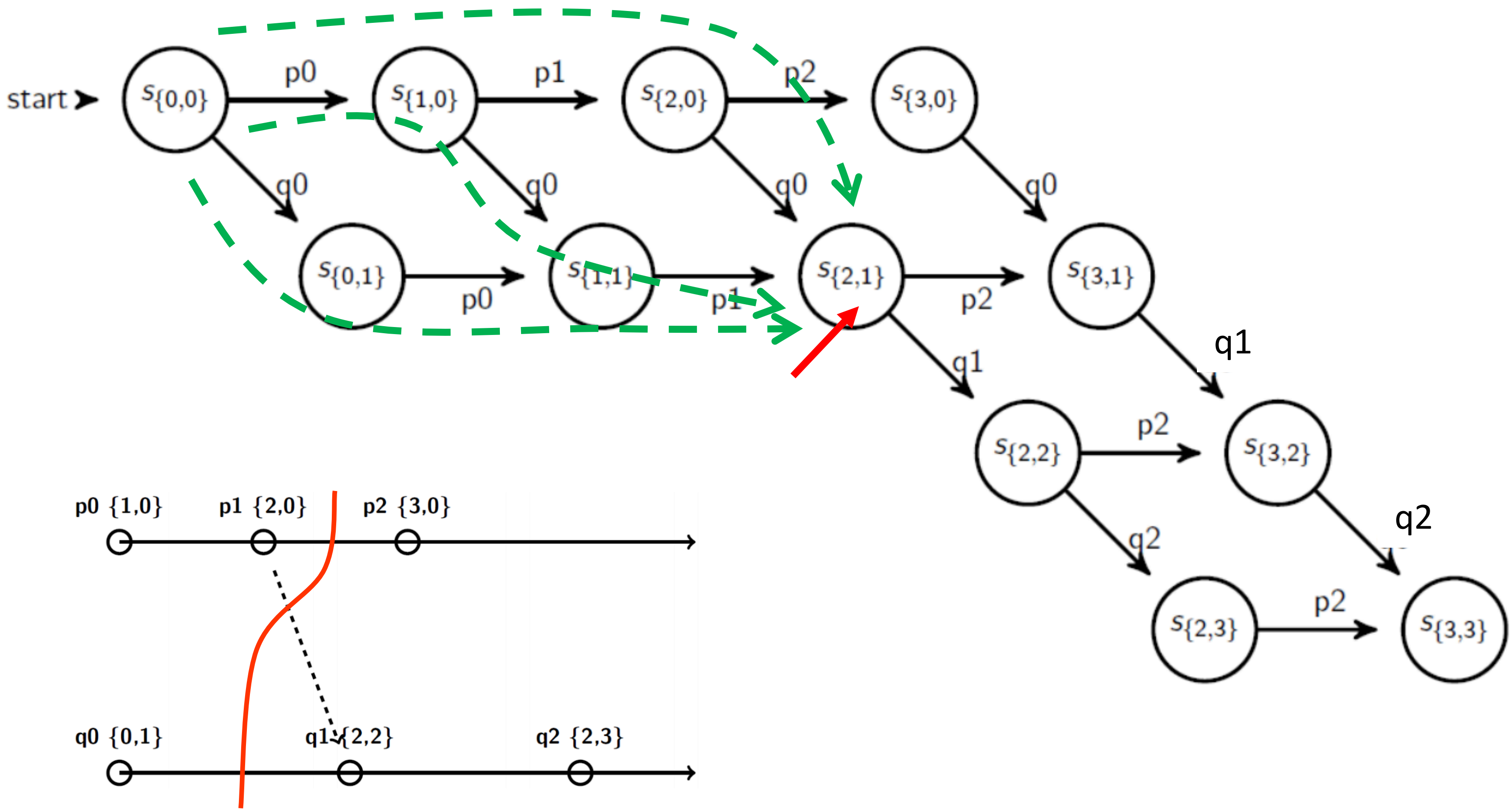

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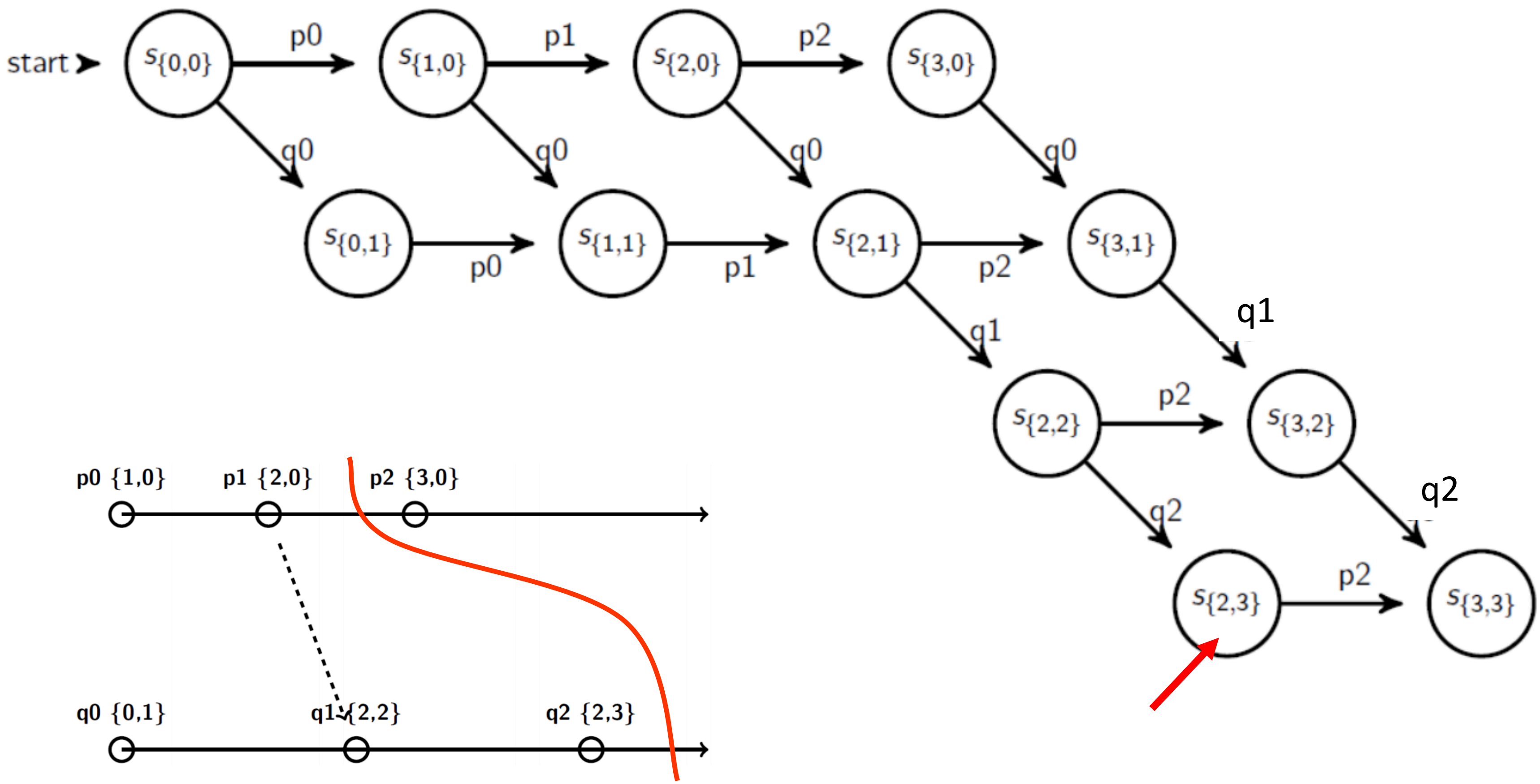

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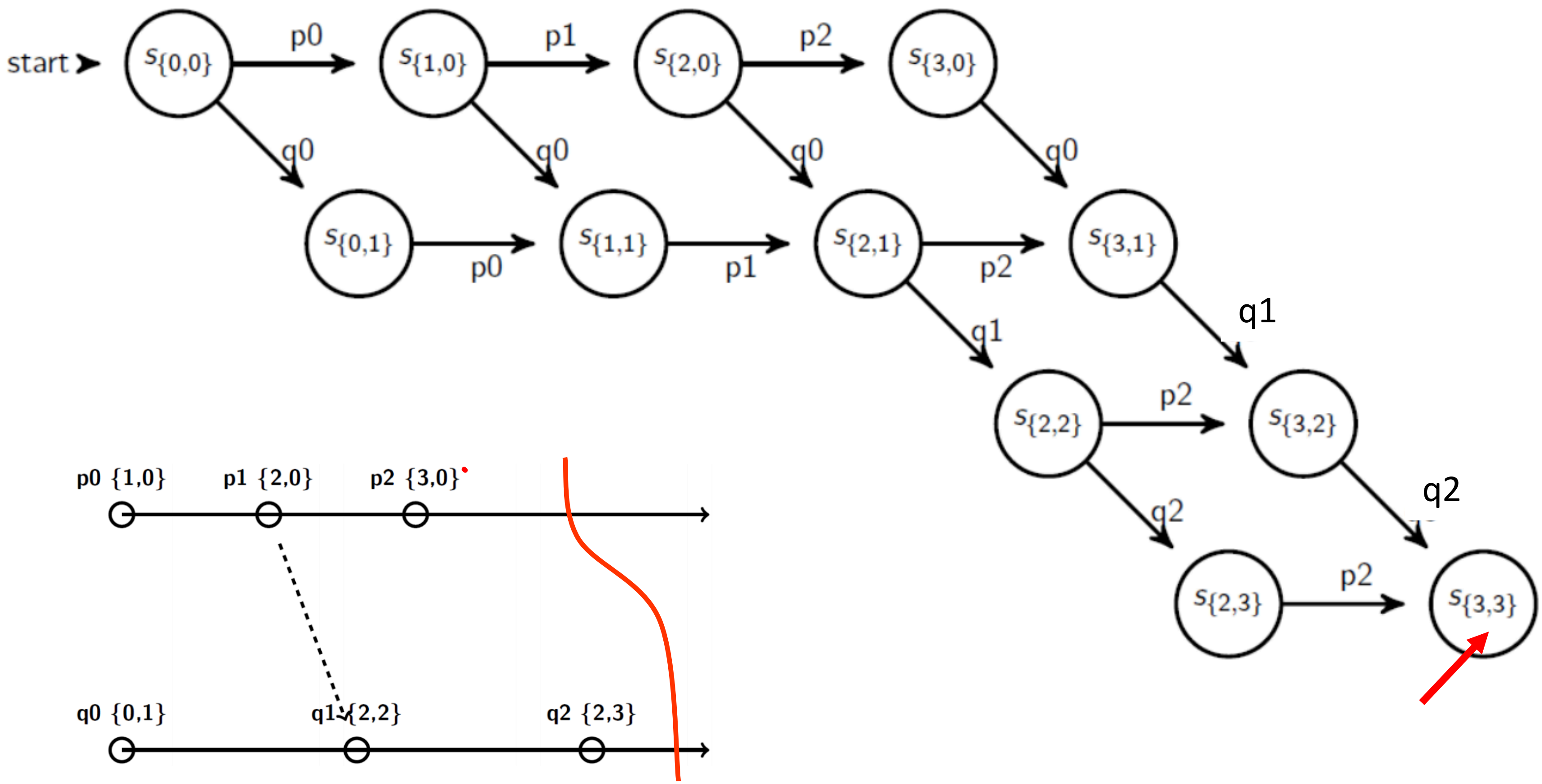

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Global State Predicates

- A global-state-predicate is a property that is *true* or *false* for a global state.
  - Is there a deadlock?
  - Has the distributed algorithm terminated?
- Two ways of reasoning about predicates (or system properties) as global state gets transformed by events.
  - Liveness
  - Safety

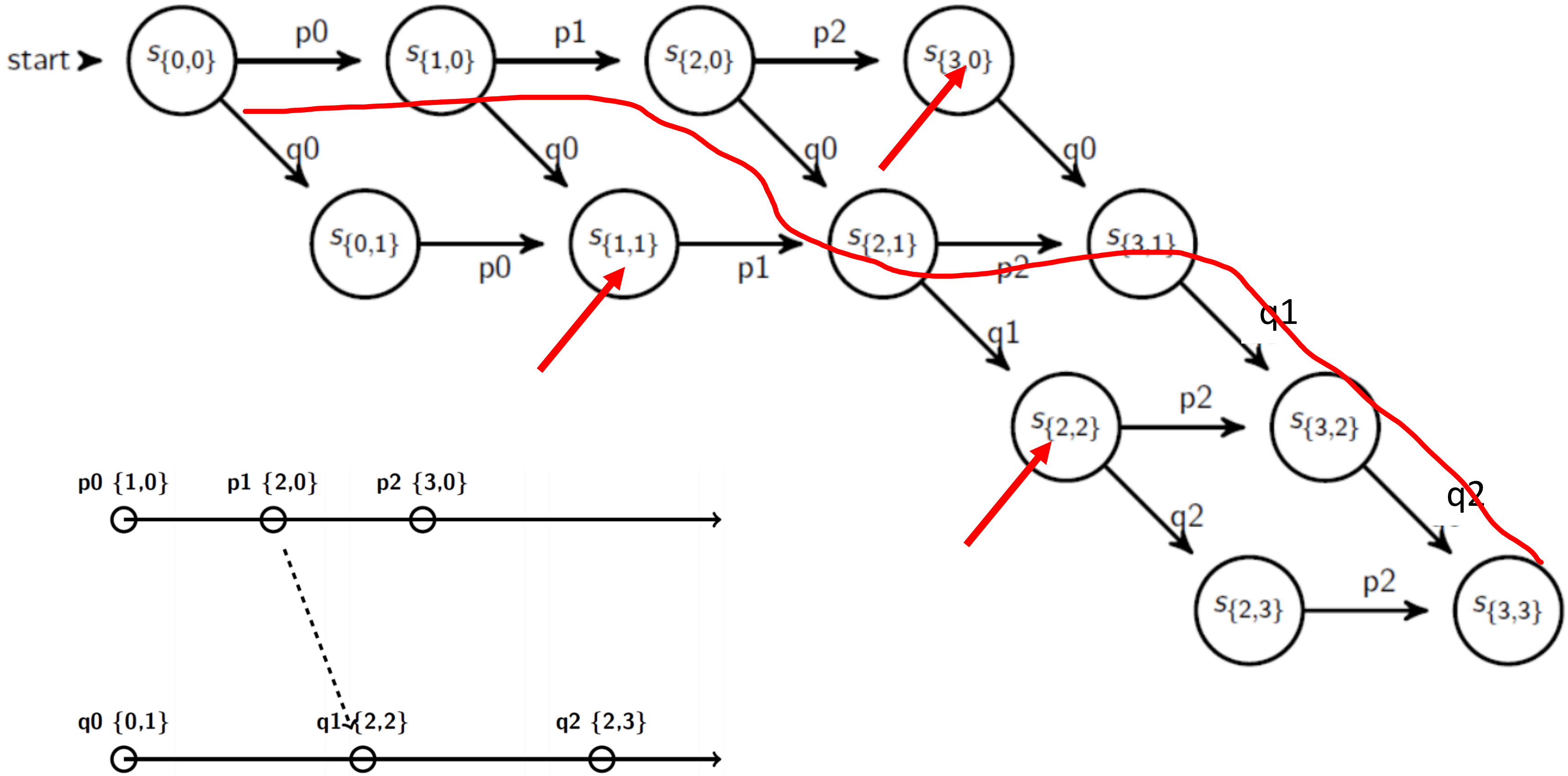
Liveness

- **Liveness = guarantee that something good will happen, eventually**
- **Examples:**
  - A distributed computation will terminate.
  - "Completeness" in failure detectors: the failure will be detected.
  - All processes will eventually decide on a value.
- A global state S_0 satisfies a **liveness** property P iff:
  - For all linearizations starting from S_0, P is true for some state S_L reachable from S_0.
  - $liveness(P(S_0)) \equiv \forall L \in$ linearizations from S_0, L passes through a S_L & $P(S_L)$ = true

Liveness Example

If predicate is true only in the marked states, does it satisfy liveness?

No



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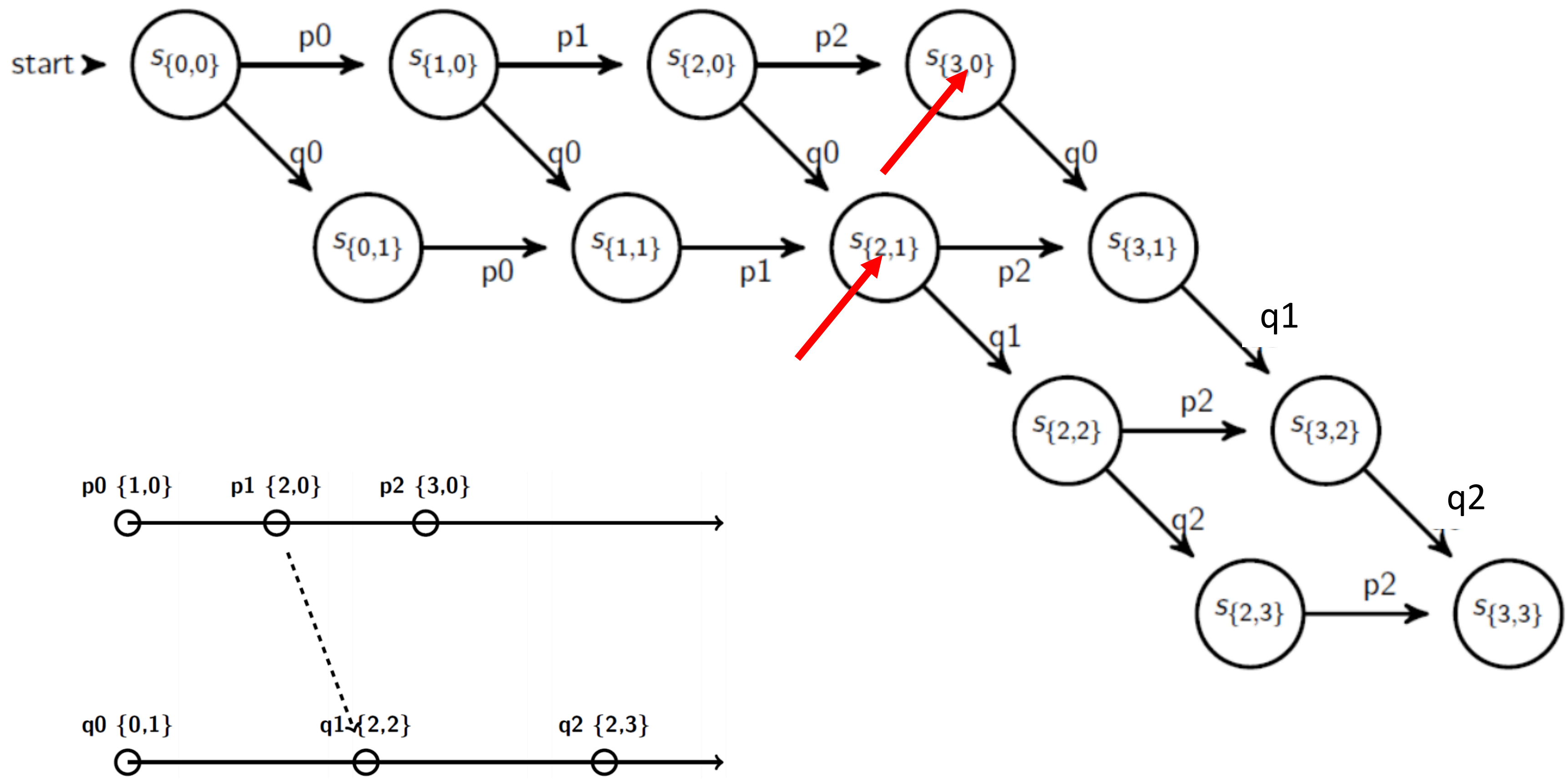

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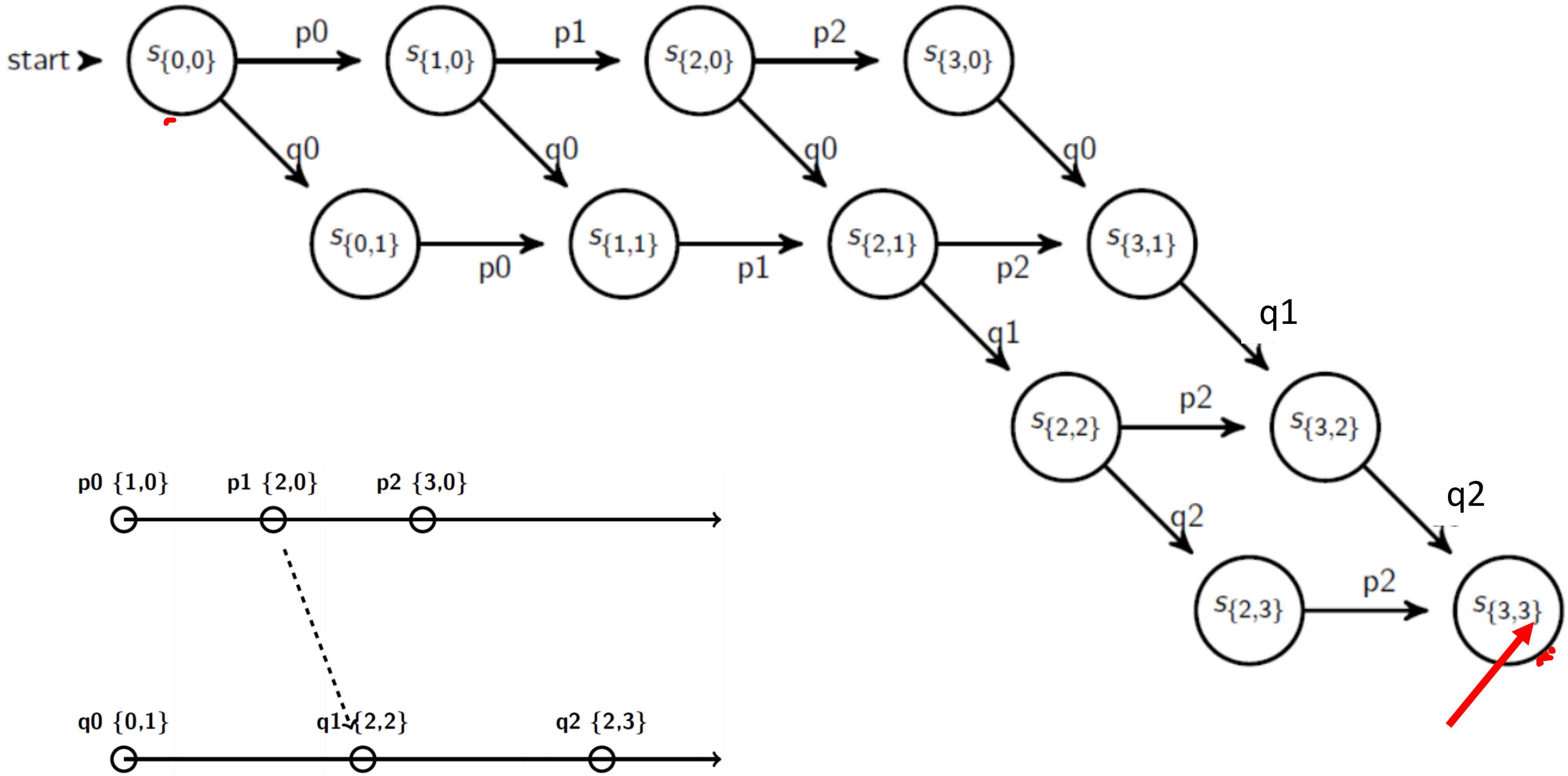

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Safety

- **Safety = guarantee that something bad will never happen.**
- **Examples:**
  - There is no deadlock in a distributed transaction system.
  - "Accuracy" in failure detectors: an alive process is not detected as failed.
  - No two processes decide on different values.
- A global state S_0 satisfies a **safety** property P iff:
  - For all states S reachable from S_0, P(S) is true.
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Safety Example

If predicate is true only in the marked states, does it satisfy safety?

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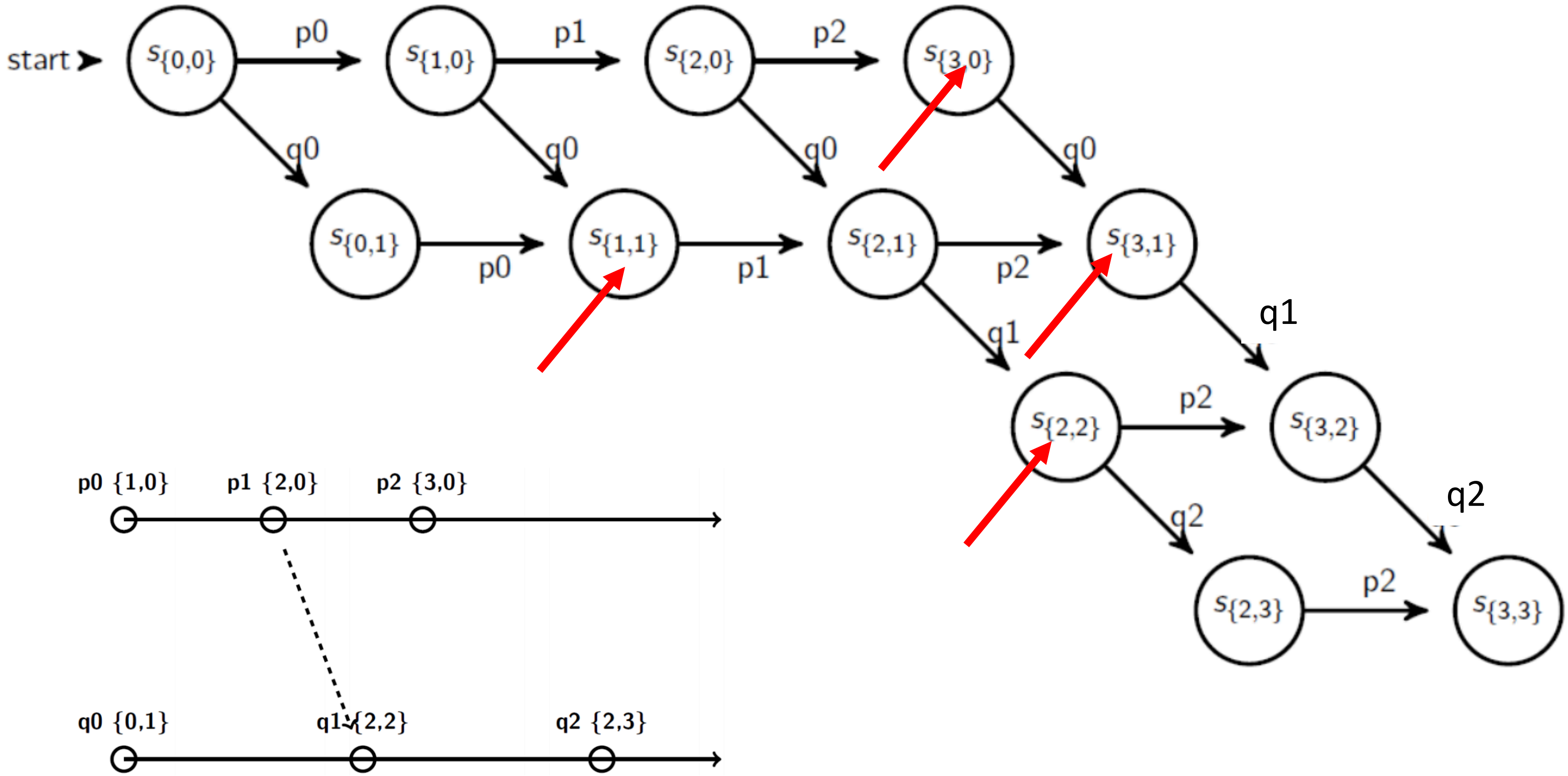
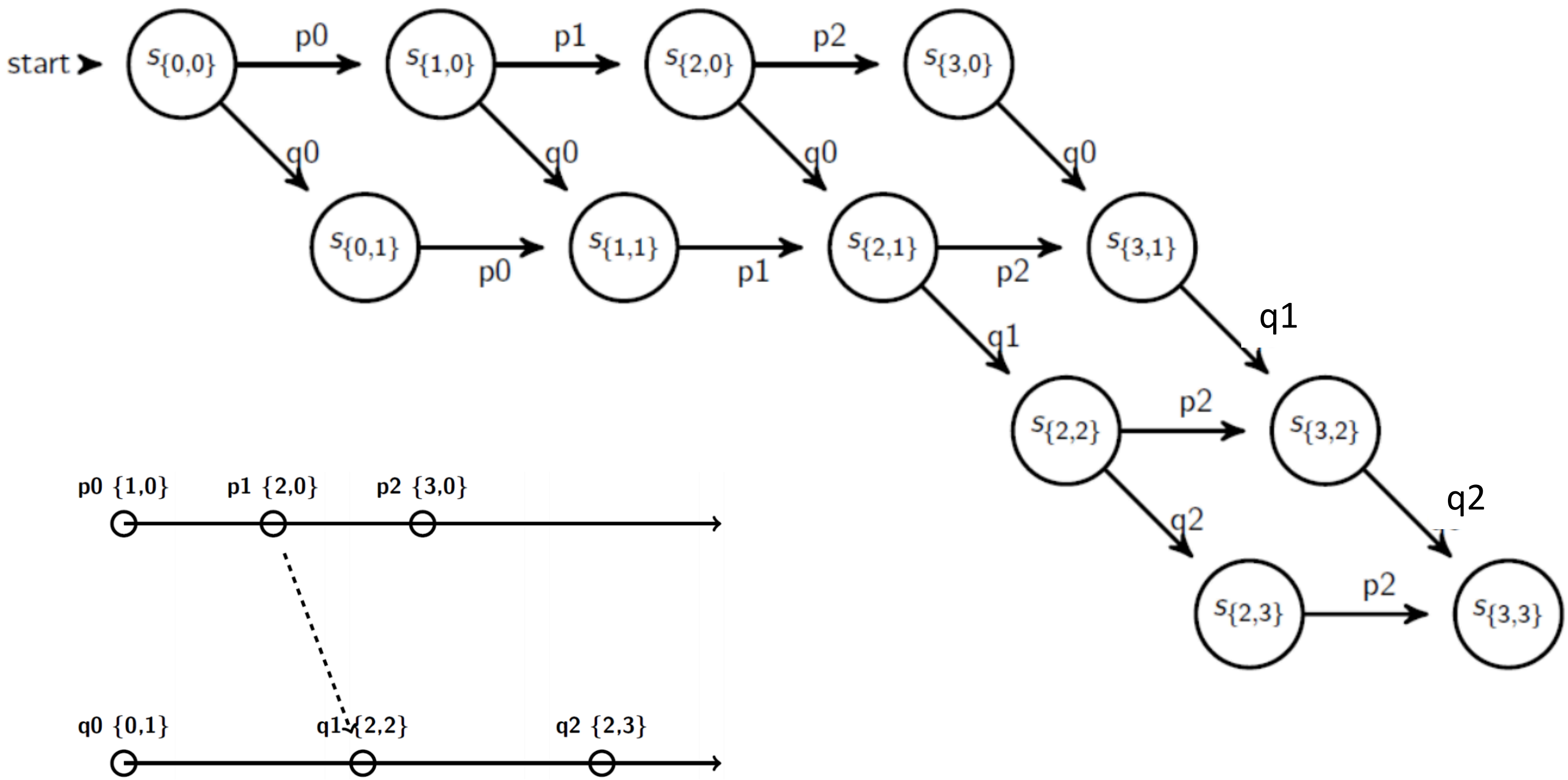


Safety Example

If predicate is true only in the **unmarked** states, does it satisfy safety?

Yes



Safety

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  - There is no deadlock in a distributed transaction system.
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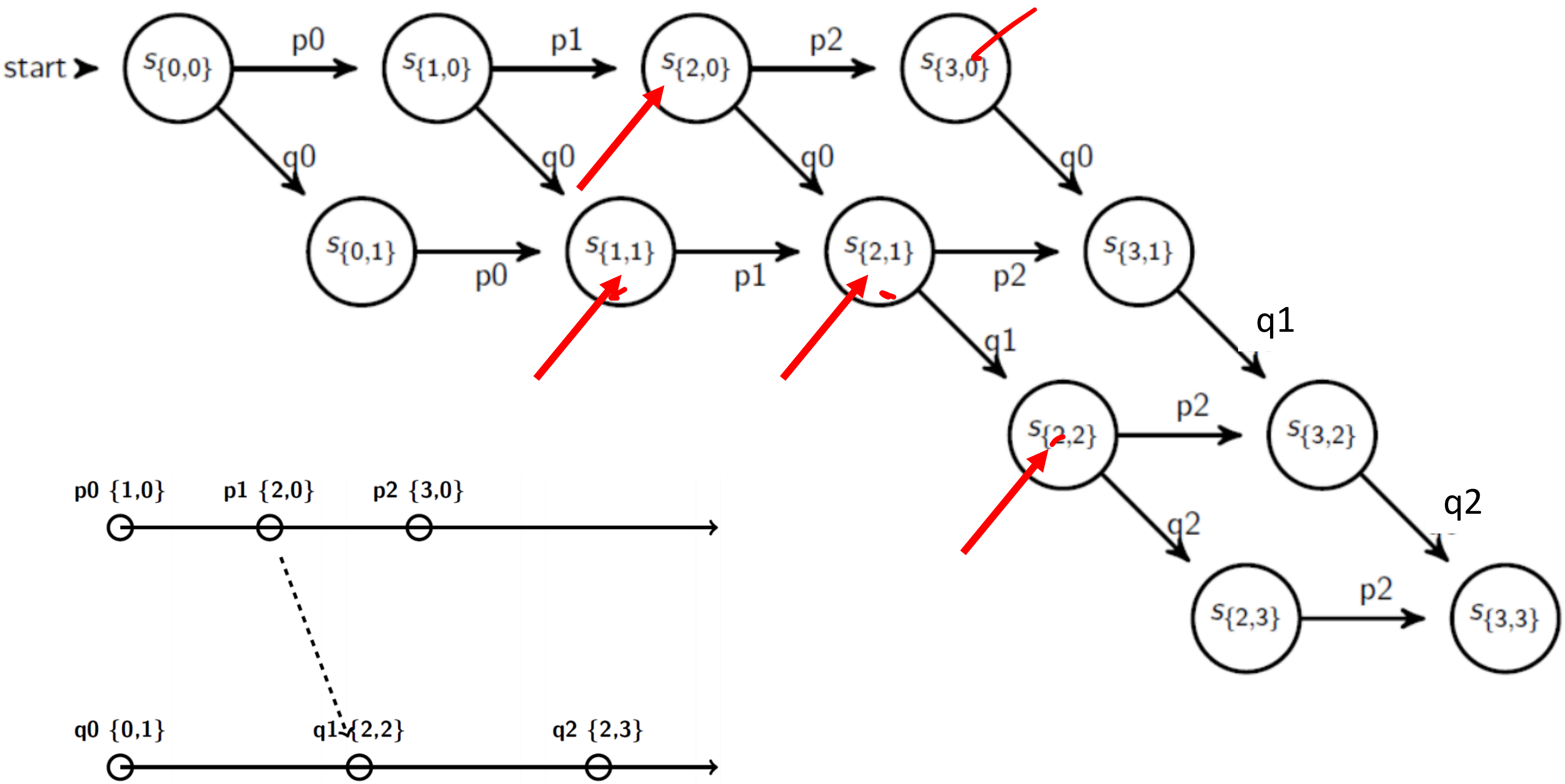
Liveness Example

Technically satisfies liveness, but difficult to capture or reason about.



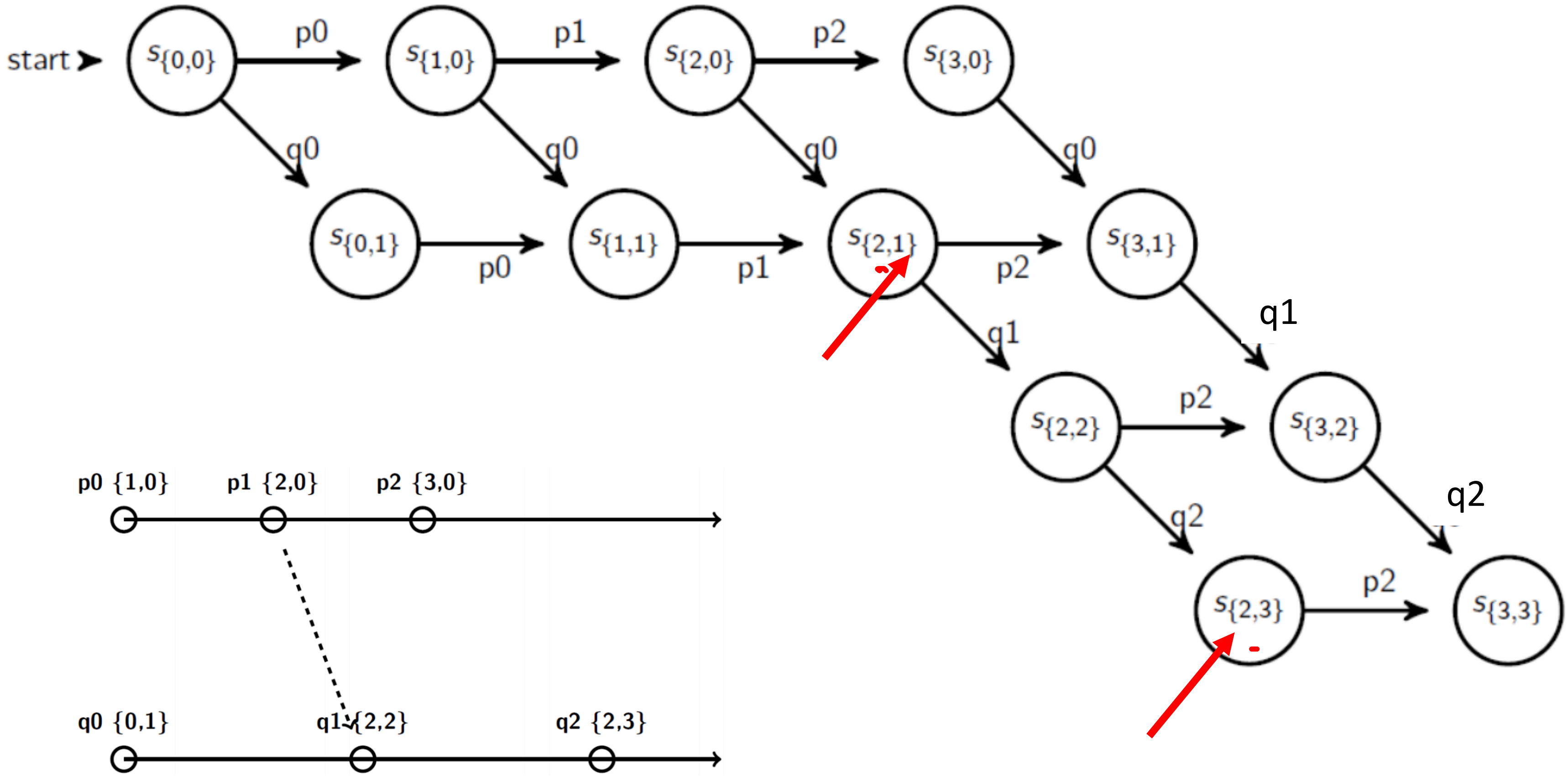
Stable Global Predicates

- once true, stays true forever afterwards (for stable liveness)

Stable Global Predicates

If predicate is true only in the marked states, is it true in a stable way?

No



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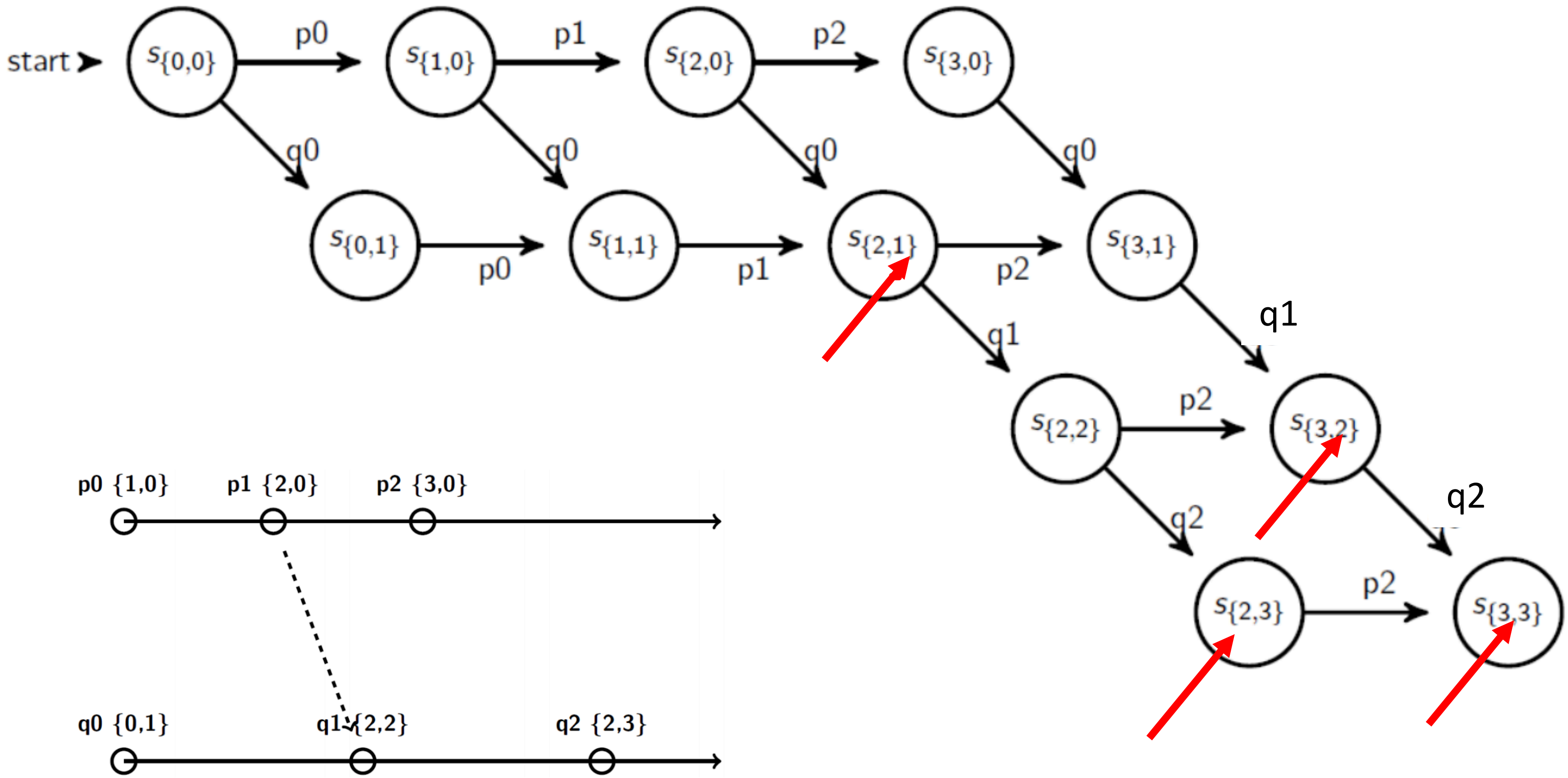

Stable Global Predicates

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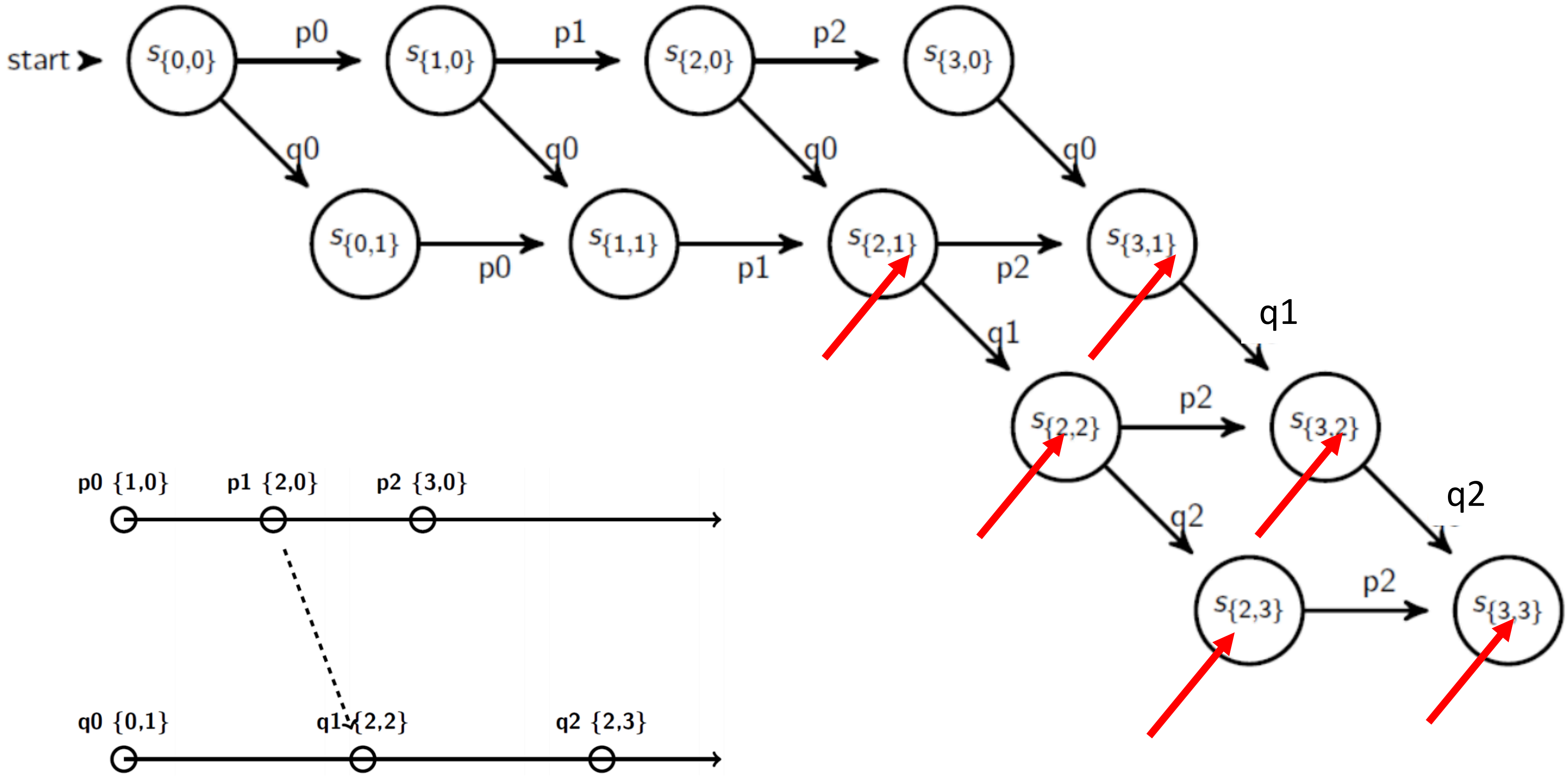


Stable Global Predicates

- once true for a state S, stays true for all states reachable from S (for stable liveness)
- once false for a state S, stays false for all states reachable from S (for stable non-safety)
- Stable liveness examples (once true, always true)
  - Computation has terminated.
- Stable non-safety examples (once false, always false)
  - There is no deadlock.
  - An object is not orphaned.
- *All stable global properties can be detected using the Chandy-Lamport algorithm.*

Global Snapshot Summary

- The ability to calculate global snapshots in a distributed system is very important.
- But don't want to interrupt running distributed application.
- Chandy-Lamport algorithm calculates global snapshot.
- Obeys causality (creates a consistent cut).
- Can be used to detect global properties.
- Safety vs. Liveness.

Today's agenda

- Global State (contd.)
  - Chapter 14.5
- Multicast
  - Chapter 15.4
  - **Goal:** reason about desirable properties for message delivery among a group of processes.

Communication modes

- **Unicast**
  - Messages are sent from exactly one process to one process.
- **Broadcast**
  - Messages are sent from exactly one process to all processes on the network.
- **Multicast**
  - Messages broadcast within a group of processes.
  - A multicast message is sent from any one process to a group of processes on the network.

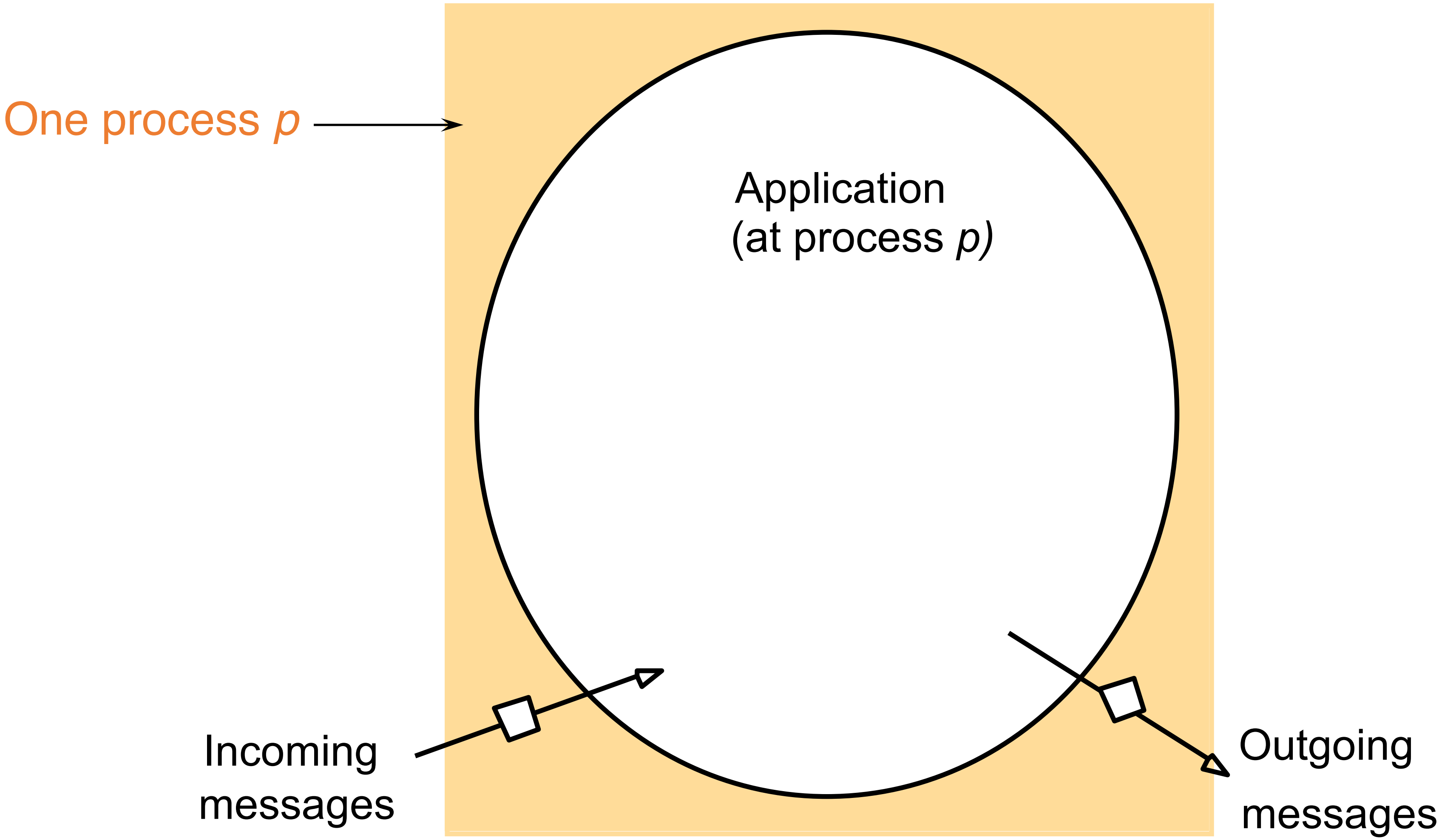
Where is multicast used?

- Distributed storage
  - Write to an object are multicast across replica servers.
  - Membership information (e.g., heartbeats) is multicast across all servers in cluster.
- Online scoreboards (ESPN, French Open, FIFA World Cup)
  - Multicast to group of clients interested in the scores.
- Stock Exchanges
  - Group is the set of broker computers.
- ……

Communication modes

- **Unicast**
  - Messages are sent from exactly one process to one process.
    - *Best effort:* if a message is delivered it would be intact; no reliability guarantees.
    - *Reliable:* guarantees delivery of messages.
    - *In order:* messages will be delivered in the same order that they are sent.
- **Broadcast**
  - Messages are sent from exactly one process to all processes on the network.
- **Multicast**
  - Messages broadcast within a group of processes.
  - A multicast message is sent from any one process to the group of processes on the network.
  - *How do we define (and achieve) reliable or ordered multicast?*

What we are designing in this class?



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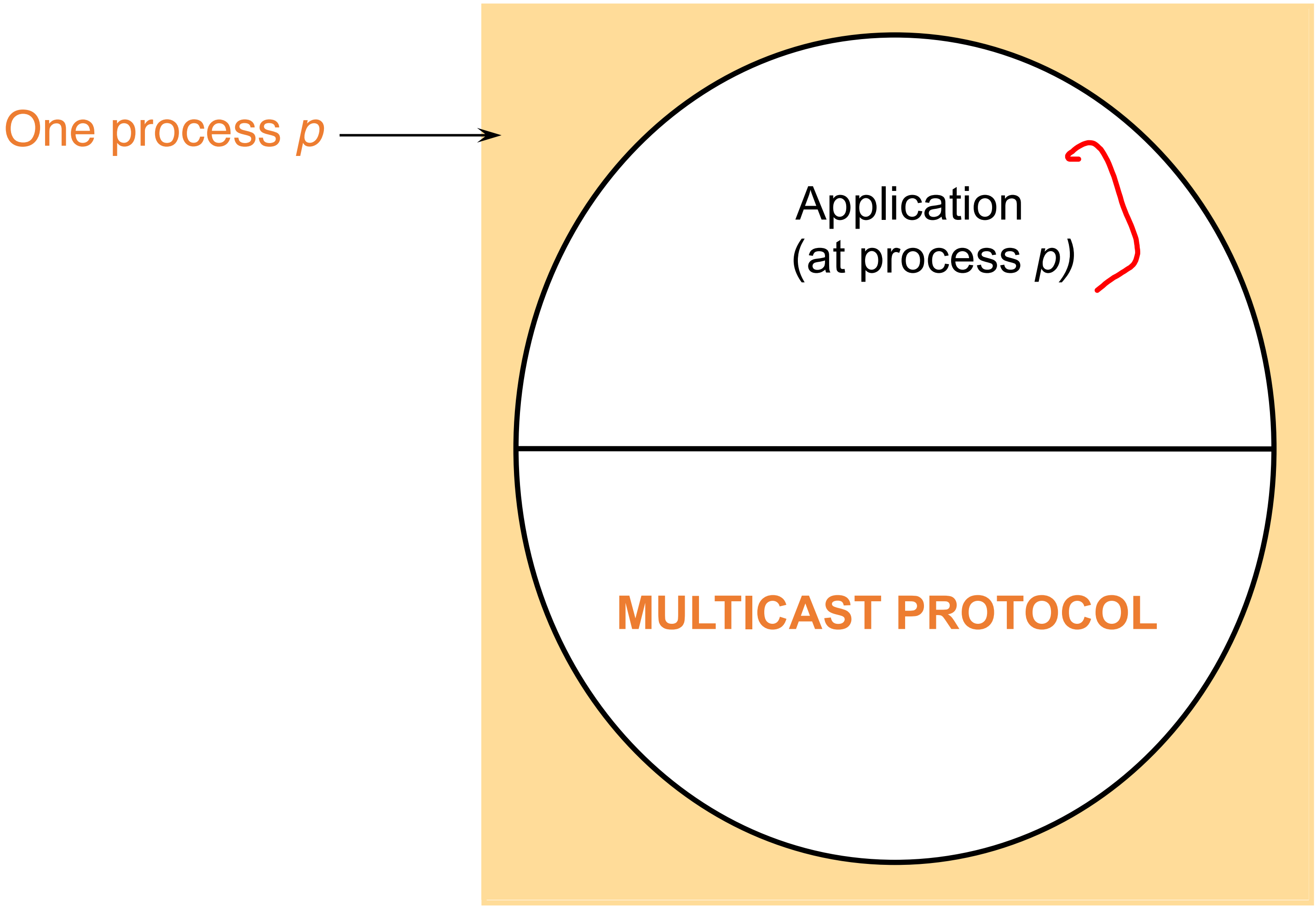

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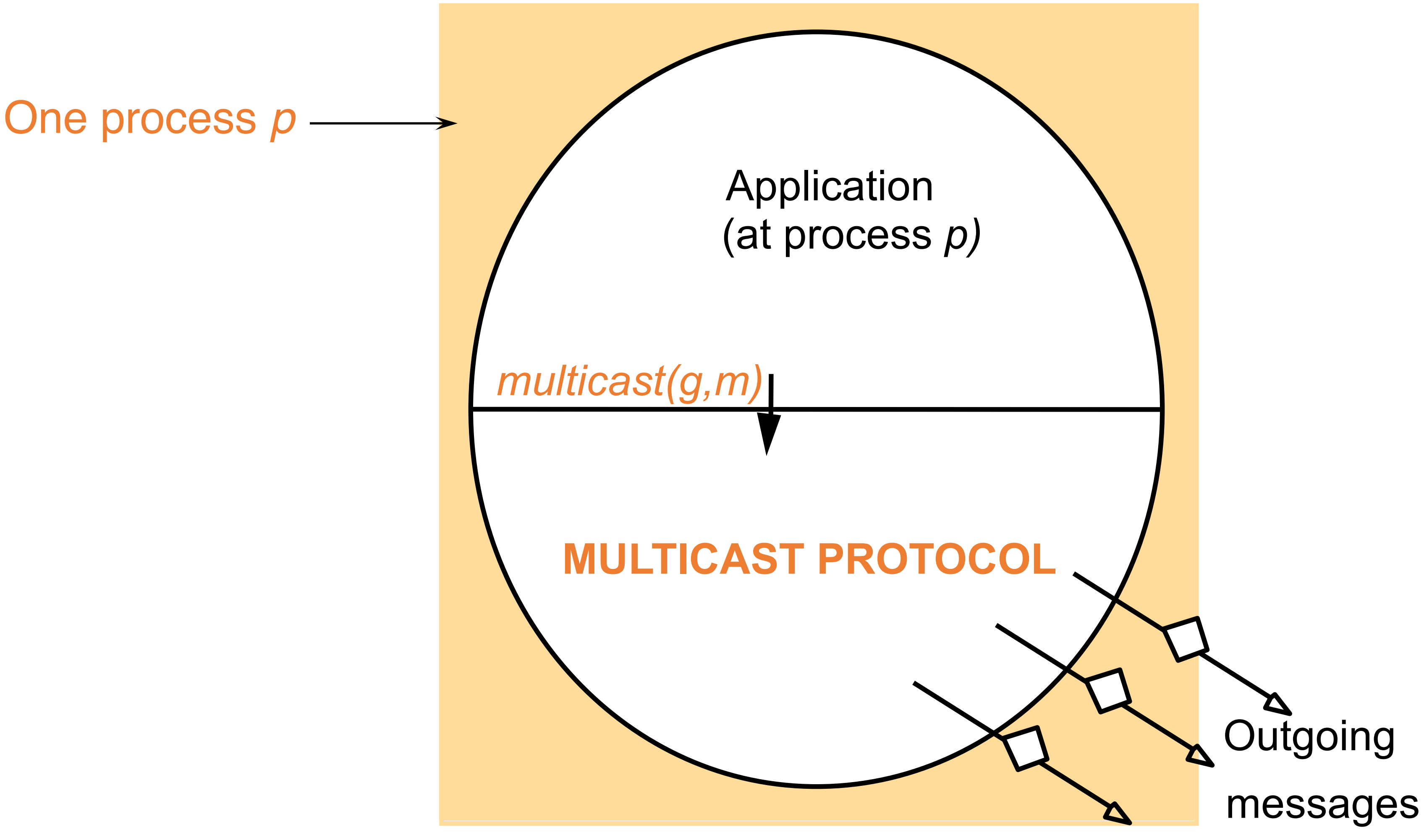

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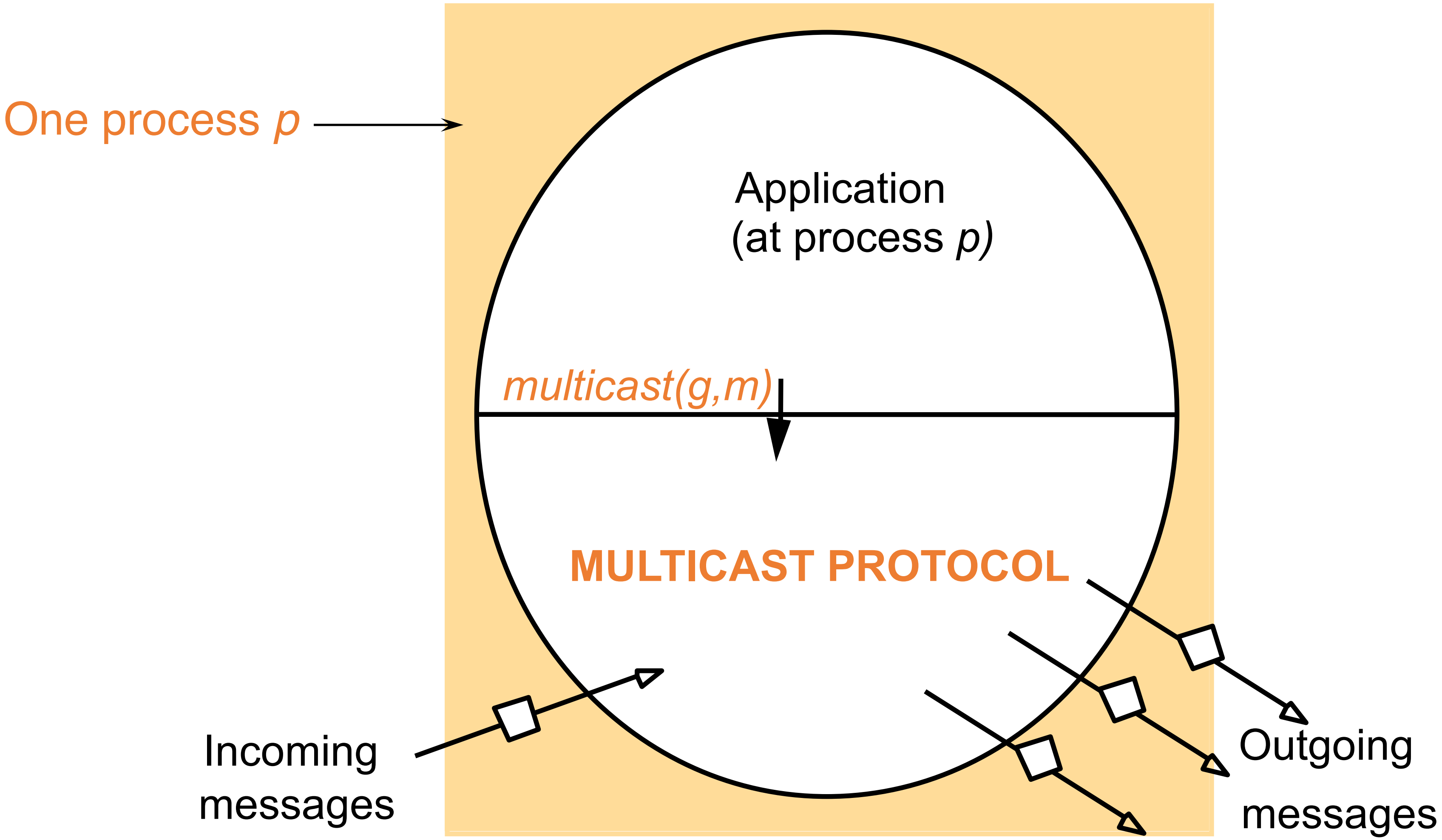

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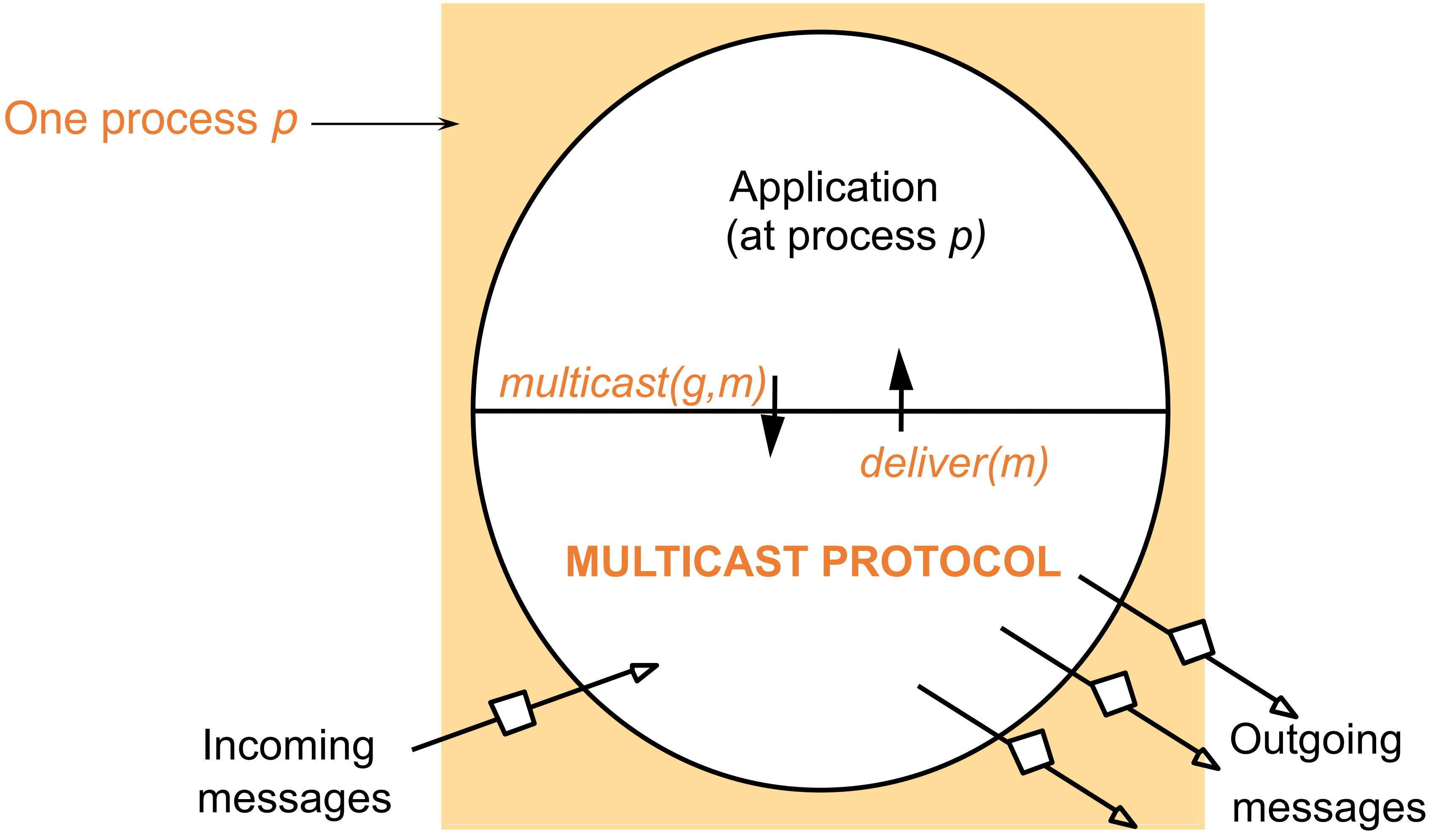

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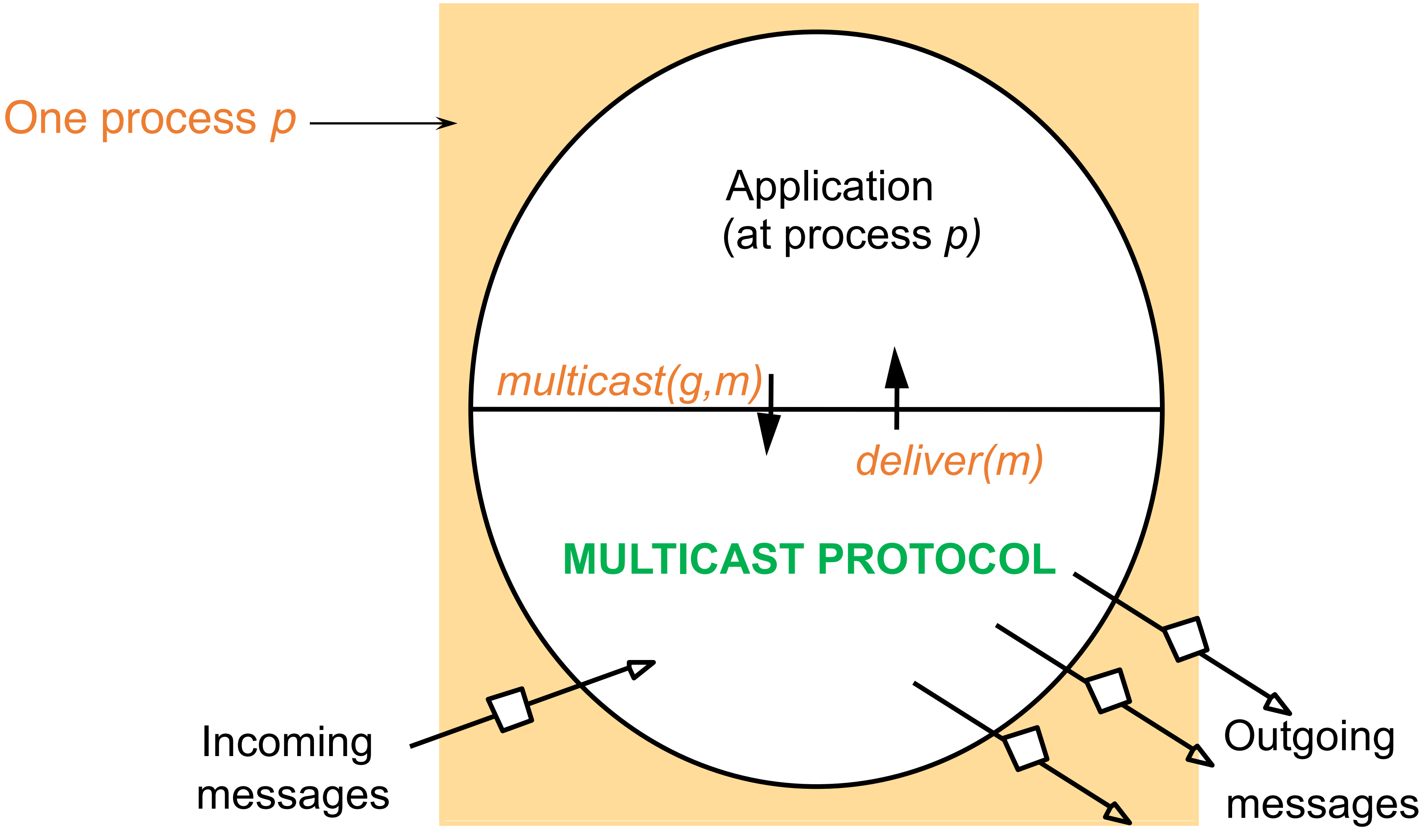

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Basic Multicast (B-Multicast)

- Straightforward way to implement B-multicast:
  - use a reliable one-to-one send (unicast) operation:

    B-multicast(group g, message m):

    for each process p in g, send (p,m).

    receive(m): B-deliver(m) at p.
- Guarantees: message is eventually delivered to the group if:
  - Processes are non-faulty.
  - The unicast "send" is reliable.
  - *Sender does not crash.*
- *Can we provide reliable delivery even after sender crashes?*
  - *What does this mean?*

Reliable Multicast (R-Multicast)

- **Integrity**: A *correct* (i.e., non-faulty) process *p* delivers a message *m* at most once.
  - *Assumption: no process sends **exactly** the same message twice*
- **Validity**: If a *correct* process multicasts (sends) message *m*, then it will eventually deliver *m* to itself.
  - *Liveness for the sender.*
- **Agreement**: If a *correct* process delivers message *m*, then all the other *correct* processes in group(*m*) will eventually deliver *m*.
  - *All or nothing.*
- Validity and agreement together ensure overall liveness: if some correct process multicasts a message *m*, then, all correct processes deliver *m* too.

How to achieve R-multicast? To be continued in next class….